

Russian Original Vol. 29, No. 2, March-April, 1994

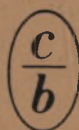
November, 1994

LITHOLOGY AND MINERAL RESOURCES

ЛИТОЛОГИЯ И ПОЛЕЗНЫЕ ИСКОПАЕМЫЕ

(LITOLOGIYA I POLEZNYE ISKOPAEMYE)

TRANSLATED FROM RUSSIAN



CONSULTANTS BUREAU, NEW YORK

LITHOLOGY AND MINERAL RESOURCES

Lithology and Mineral Resources is abstracted or indexed in *Chemical Abstracts*, *Engineering Index*, and *Metal Abstracts Index*.

Mailed in the USA by Publications Expediting, Inc., 200 Meacham Avenue, Elmont, NY 11003.

POSTMASTER. Send address changes to *Lithology and Mineral Resources*, Plenum Publishing Corporation, 233 Spring Street, New York, NY 10013.

Lithology and Mineral Resources is a translation of *Litologiya i Poleznye Iskopaemye*, a publication of the Russian Academy of Sciences.

Editorial Board of *Litologiya i Poleznye Iskopaemye*:

Editor: V. N. Kholodov

Associate Editors: B. M. Mikhailov and P. P. Timofeev

Secretary: G. Yu. Butuzova

A. N. Dmitrievskii
V. I. Kononov
A. I. Konyukhov
A. A. Migdisov
I. O. Murdmaa

V. I. Sedletskii
E. F. Shnyukov
S. A. Sidorenko
I. I. Volkov
O. V. Yapaskurt

Copyright © 1994, Plenum Publishing Corporation. *Lithology and Mineral Resources* participates in the Copyright Clearance Center (CCC) Transactional Reporting Service. The appearance of a code line at the bottom of the first page of an article in this journal indicates the copyright owner's consent that copies of the article may be made for personal or internal use. However, this consent is given on the condition that the copier pay the flat fee of \$12.50 per article (no additional per page fees) directly to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, Massachusetts 01923, for all copying not explicitly permitted by Sections 107 or 108 of the U.S. Copyright Law. The CCC is a nonprofit clearinghouse for the payment of photocopying fees by libraries and other users registered with the CCC. Therefore, this consent does not extend to other kinds of copying, such as copying for general distribution, for advertising or promotional purposes, for creating new collective works, or for resale, nor to the reprinting of figures, tables, and text excerpts. 0024-4902/94/\$12.50

Consultants Bureau journals appear about six months after the publication of the original Russian issue. For bibliographic accuracy, the English issue published by Consultants Bureau carries the same number and date as the original Russian from which it was translated. For example, a Russian issue published in December will appear in a Consultants Bureau English translation about the following June, but the translation issue will carry the December date. When ordering any volume or particular issue of a Consultants Bureau journal, please specify the date and, where applicable, the volume and issue number of the original Russian. The material you will receive will be a translation of that Russian volume or issue.

Subscription (6 Issues):

Vol. 28: \$1150 (domestic); \$1345 (foreign) Single issue: \$200
Vol. 29: \$1195 (domestic); \$1395 (foreign) Single Article: \$12.50

CONSULTANTS BUREAU, NEW YORK AND LONDON



233 Spring Street
New York, New York 10013

Lithology and Mineral Resources (0024-4902/94/\$12.50). Published bimonthly by Consultants Bureau, a division of Plenum Publishing Corporation, 233 Spring Street, New York, NY 10013. Annual Subscription price is \$1195 (domestic) and \$1395 (foreign). Second-class postage paid at Jamaica, New York 11431.

LITHOLOGY AND MINERAL RESOURCES

A translation of *Litologiya i Poleznye Iskopaemye*

November, 1994

Volume 29, Number 2

March-April, 1994

CONTENTS

Engl./Russ.

Sulfide Formation in the Region of Contemporary Peat Accumulation in the Rioni Intermontane Trough. Communication 2. Patterns of Pyrite Distribution in Peat Bogs of the Coastal-Continental Strip of Colchis - P. P. Timofeev, L. I. Bogolyubova, and L. Ya. Kizil'shtein	97	3
Sediments of the Contemporary Dried-Up Bottom of the Aral Sea, Their Diagenesis and Effect on the Ecology of the Aral Region - I. V. Rubanov	109	17
The Evolution of Sedimentary Basins in Continent-Island Arc Collision Zones - A. I. Konyukhov	121	31
The Salop-Gilluly Curve. Reality or Artifact? - V. N. Kholodov	134	49
Post-Sedimentary Variations of Devonian Deposits of the Central Timan Mountain Range - I. M. Simanovich and V. V. Kostyleva	148	66
Thermodynamic Modeling of Hydrochemical Processes in the Persalt Series in the Area of the Upper Kama River - V. P. Zverev and L. V. Migunov	158	78
Formation Conditions of Ore-Bearing Facies and Detrital Ores of the Korbalikh Polymetallic Pyrite Deposits, Altai Ore Range (Rudnyi Altai Mts.) - A. G. Kuznetsov, A. G. Zlotnik-Khotkevich, and V. M. Chekalin	165	86
Discovery of Gold Deposits in Ancient Conglomerates in Russia - A. A. Konstantinovskii	177	102
Isotopic Composition of Oxygen in Danburities from Later-Jurassic Gypsum-Anhydrite Rocks of Southeastern Turkmenistan - V. N. Svedov and Z. D. Kuliev	192	134
In Honor of the Eightieth Birthday of A. B. Ronov	194	138
In Honor of the Seventy-Fifth Birthday of P. P. Timofeev	197	140
Vladimir Viktorovich Burkov	199	142

The Russian press date (podpisano k pechati) of this issue was 3/5/1994. Publication therefore did not occur prior to this date, but must be assumed to have taken place reasonably soon thereafter.

SULFIDE FORMATION IN THE REGION OF CONTEMPORARY PEAT ACCUMULATION IN THE RIONI INTERMONTANE TROUGH.

COMMUNICATION 2. PATTERNS OF PYRITE DISTRIBUTION IN PEAT BOGS OF THE COASTAL-CONTINENTAL STRIP OF COLCHIS

P. P. Timofeev, L. I. Bogolyubova, and L. Ya. Kizil'shtein UDC 552.14:549.3:553.97(479)

Data are given on the distribution of iron sulfides in peat deposits of Colchis, which is a region of peat accumulation in the Rioni intermontane trough. It was established that increased concentrations of iron sulfides are consistently confined to genetic types of sediments in peat deposits of the coastal-continental strip near the mouths of rivers. The genetic unity of processes of sulfide formation and sedimentation in conditions of contemporary and ancient peat accumulation was shown.

CONTENT AND DISTRIBUTION OF IRON IN SEDIMENTS OF PEAT DEPOSITS IN THE COLCHIAN LOWLAND

Iron is a secondary component of the sulfide mineralization of sediments in peat deposits of Colchis under consideration here [6, 7]. As investigations have shown, its total content in sediments of peat deposits varies in the range of 4-6%, deviating in individual specimens in the direction of a decrease to less than 3% and an increase up to 14% (Table 1). In the suspended matter and bottom clay of the Rioni River, which feeds regions of peat accumulation adjacent to it, iron is found in the range of 6-7%. In the salt composition of river and lake waters of the Colchian lowland, the iron content is very low and is only determined from 0.02 to 0.5 mg/liter, and sometimes a little more (0.1 mg/liter). In bog waters, the iron content is even lower in comparison with river waters and amounts to about 0.01-0.02 mg/liter, sometimes rising to 0.03-0.04 mg/liter. In peat-forming plants, iron is found in a comparatively small amount (Table 2). There is somewhat more of it in the roots and noticeably less in the vegetative organs. Different peat-forming plants are characterized by different iron contents. In the composition of reed there is 2.57% of it, and approximately as much in alder trunks (see Table 2). The greatest amount (3.53%) of iron is noted in sphagnum mosses. The total content of it in the sediments of peat deposits is made up of "constitutional" iron, which is inherent in peat-forming plants, and iron entering together with surface and ground water feeding the peat bog, in a suspended, as well as in a dissolved state, including in organomineral complexes.

Iron, as is known [6], is one of the elements the forms of existence of which are the most sensitive indicators of diagenetic transformation of sediments. Therefore, it is especially interesting to trace changes in the forms of iron in contrasting facies of regions of peat accumulation, including a number of genetic types of sediments (from peats to peaty clays and clays) containing a comparatively small amount of reactive organic matter. Investigations on the distribution of contents of ferric and ferrous forms of iron in cross sections of peat deposits showed their clear dependence on genetic types of sediments, in particular, on the content of plant material in them that has undergone changes in the process of gelation. In the composition of suspended matter in the Rioni River, which is the supplier of iron to adjacent peat bogs, the ferric form of iron is sharply predominant, amounting to 9.58%, while the ferrous form only accounts for 0.36% (see Table 1). As the content of plant material increases in the sediment of a given genetic type, the content of ferrous iron increases at the expense of ferric. Thus, in clays containing up to 25% gelled organic matter, the concentration of ferrous iron reaches 4%, but ferric iron is still sharply predominant (see Table 1). In clays with woody gelinite-precollinite or gelinite-posttelnite peat (peaty and very peaty), ferrous forms, as a rule, begin to predominate over ferric forms to a greater or lesser degree. In woody gelinite-precollinite and posttelnite peats, in which plant matter constitutes 50 to 85% (clayey and very clayey peats), ferric forms are only preserved in the range of 1%, occasionally 2%, or they disappear entirely, and ferrous forms represent all of the iron found in that peat.

TABLE 1. Iron Content in Sediments of Peat Bogs in the Poti and Guri Basins of the Colchian Lowland

Number of bore-hole (in numerator), number of specimens (in denominator)	Depth, m	Genetic type of sediment	Fe ₂ O ₃	FeO	pH	Fe _{tot}
			% of air-dry matter			
Anaklia deposit						
$\frac{7}{126}$	0,50	Woody, gelinite-precollinite, very clayey peat	0,14	7,25	4,17	5,73
$\frac{7}{128}$	1,00	Clay with woody attritus (peaty subsoil)	4,10	4,45	6,2	6,33
$\frac{7}{131}$	1,75	Fine-grained silt with humus (peaty subsoil)	7,80	3,57	6,5	8,24
$\frac{7}{139}$	4,75	Clay with woody gelinite-precollinite peat (very peaty soil)	1,74	5,33	4,8	5,36
$\frac{80}{911}$	6,00	Woody, gelinite-precollinite, very clayey peat	0,86	11,86	5,60	9,63
$\frac{202}{2}$	2,20	Sedge-reed, gelinite-precollinite, clayey peat	0,07	4,98	4,90	3,92
$\frac{202}{8}$	5,35	The same	Her	6,01	4,50	4,68
Nabad deposit						
$\frac{98}{25}$	0,50	Rhizoid-sedge, gelinite-telinite, clayey peat with gelinite-precollinite	*	6,20	5,05	4,82
$\frac{98}{359}$	4,25	Sedge-woody, gelinite-posttelinite, very clayey peat	1,84	3,84	4,30	4,28
$\frac{43}{646}$	2,00	The same	1,02	6,33	4,60	5,55
$\frac{43}{654}$	5,85	Clay with herbaceous plant remains, carbonate	5,22	3,75	8,4	6,57
$\frac{43}{655}$	6,00	Sedge-reed, gelinite-precollinite, very clayey peat	1,00	7,46	6,35	6,50
$\frac{43}{656}$	6,50	Coarse-grained silt with woody attritus, carbonate	7,55	3,69	8,20	8,16
$\frac{100}{22}$	5,00	Clay with gelinite-precollinite reed peat (soil)	3,56	3,53	4,50	5,24
$\frac{100}{24}$	6,00	Clay with reed gelinite-precollinite peat	4,56	12,06	5,00	14,37
$\frac{90}{202}$	0,50	Woody, gelinite-precollinite, very clayey peat	0,50	4,90	4,92	4,16
$\frac{90}{198}$	1,00	Clay with woody, gelinite-precollinite peat (very peaty)	0,46	5,60	5,25	4,68
$\frac{99}{1030}$	0,50	Woody, gelinite-precollinite, clayey peat	Her	7,06	4,20	5,49
$\frac{12}{218}$	0,25	Clay with woody, gelinite-precollinite peat (very peaty)	2,11	1,69	4,95	2,79
$\frac{12}{222}$	1,00	Clay with woody plant remains	5,72	2,85	5,11	6,22

Table 1 (continued)

Number of bore-hole (in numerator), number of specimens (in denominator)	Depth, m	Genetic type of sediment	Fe ₂ O ₃	FeO	pH	Fe _{tot}
			% of air-dry matter			
Poti deposit						
$\frac{123}{206}$	0,25	Clay with sedge-reed, gelinite-precollinite peat (very peaty)	1,12	5,48	7,32	—
Pichora deposit						
$\frac{118}{145}$	0,40	Woody, gelinite-telinite peat, very sandy	0,66	4,32	—	3,82
$\frac{200}{2}$	0,50	Woody, gelinite-posttelinite, very clayey peat	Her	8,61	4,40	6,70
$\frac{200}{5}$	0,85	Woody, gelinite-precollinite, slightly clayey peat	1,14	5,28	4,75	4,91
$\frac{200}{67}$	2,50	The same	0,16	7,35	4,50	5,83
$\frac{201}{2}$	0,70	Woody, gelinite-posttelinite peat	1,47	6,60	—	5,76
$\frac{201}{3}$	1,50	Woody, gelinite-precollinite peat	1,41	4,83	—	4,74
$\frac{201}{4}$	2,00	Woody, gelinite-precollinite peat	1,13	8,4	—	7,08
$\frac{201}{5}$	2,50	The same	0,60	7,29	—	6,09
Imnat deposit						
$\frac{102}{56}$	0,50	Clay with woody, gelinite-precollinite peat (very peaty)	3,29	5,08	4,55	6,26
$\frac{116}{127}$	4,00	Sedge-reed, gelinite-precollinite peat	1,12	5,48	4,87	7,62
Moltakva deposit						
$\frac{125}{245}$	2,00	Clay with woody attritus (slightly peaty)	6,91	1,07	6,00	5,67
$\frac{243}{257}$	7,50	Clay with woody attritus	10,68	1,11	5,84	8,34
$\frac{125}{260}$	8,50	Clay with woody gelinite-posttelinite peat (very peaty)	4,44	4,98	5,70	6,98
$\frac{115}{111}$	2,00	The same	6,30	4,19	—	7,67
Kobuleti deposit						
$\frac{15}{279}$	4,75	Clay with woody, gelinite-precollinite peat and diatoms (very peaty)	5,20	2,20	4,14	5,35
$\frac{15}{301}$	5,25	Clay with lumpy structure, rootlets, woody attritus, humus, and diatoms (soil)	5,93	2,48	3,50	6,08
$\frac{15}{306}$	6,50	Clay with woody attritus, diatoms	6,00	2,90	3,55	6,46
Rioni River		Suspended matter (according to M. A. Rateev)	9,58	0,36	—	6,99
1024	—	Bottom clay	9,16	0,33	—	6,67

The data given confirm that the completeness of reduction of iron in various genetic types of sediments in peat bogs is determined by the amount of reactive plant material contained in them. This becomes obvious from the following examples (see Table 1). Thus, in borehole 7 (Anaklia deposit), at a depth of 4.75 m, in clay with woody gelinite-precollinite peat (specimen 139, very peaty), 1.74% ferric iron was preserved. At the same time, in woody, gelinite-precollinite, very clayey peat (specimen 126) lying at a depth of only 0.5 m in the same borehole the content of ferric iron is insignificant (0.14%). In many cases, in peats with ash content of no more than 35% (slightly clayey and clayey peats), at a depth of 0.5 m iron hydroxides are completely reduced (borehole 98, specimen 25, and borehole 99, specimen 1030 of the Nabad deposit; borehole 200, specimen 2 of the Pichora deposit, etc.), while in clays containing sometimes more, sometimes less organic matter in the form of peat or dispersed plant remains, even in deep horizons of the deposit, a fairly large amount of iron hydroxides is preserved (borehole 125, specimens 245, 257, and 260 of the Moltavka deposit; borehole 15, specimens 279, 301, and 306 of the Kobuleti deposit, etc.).

The examples given indicate that the effect of the amount of organic matter in sediment of the same genetic type is so great that the factor of the length of the sediment's existence, determined by the relative depth of its occurrence, is leveled out, as a rule. In connection with this, in the conditions of peat deposits composed of various genetic types of sediments, zones are distinguished with more or less complete conversion of the ferric form of iron in the process of the sediment's diagenesis.

More detailed study of the mineral forms of iron in a number of boreholes showed that the greater part of it is made up of bi- and trivalent forms soluble in 2% HCl. Conversion to reactive forms of iron ($\text{Fe}^{2+} + \text{Fe}^{2+}\text{HCl}^- + \text{Fe}^{3+}\text{HCl}^-$) lets us think that the ratio of bi- and trivalent iron soluble in hydrochloric acid is determined by the genetic type of sediment containing a particular amount of organic matter. As the organic-matter content increases in the series of genetic types of sediments from clay with plant remains, attritus, and humus to clay with gelinite-precollinite peat of any botanical composition and on to peat, the amount of bivalent iron soluble in HCl rises.

The amount of pyrite iron in the overall balance of reactive iron varies in a wide range (from 0.4 to 5.5%) and is small (Table 3). In this case, no noticeable changes are observed in the contents of it depending on the depth of occurrence of a given genetic type of sediment, or on the amount of admixture of organic matter in it. This is understandable, since the appearance and concentration of pyrite iron in the sediment is regulated primarily by the concentration of sulfate ions and the development of sulfate-reducing bacteria in it. Thus, the iron in the sediments of peat deposits does not limit the process of sulfide mineral formation, since this element, as is known, is not scarce, and its reactive form is always present in sediments containing decomposing organic matter.

MORPHOLOGY OF INCLUSIONS OF IRON SULFIDES IN SEDIMENTS OF PEAT DEPOSITS

Fairly numerous references to the presence of iron sulfides (pyrite and marcasite) in peat deposits were not accompanied by special investigations of them. Meanwhile, this question deserves attention, if only for comparison with sulfide inclusions in other types of sediments and coal seams, which have been considerably more fully studied in this regard. As investigations showed, the iron sulfides in peat deposits of Colchis are represented by two forms, of which pyrite (iron disulfide FeS_2) is sharply predominant, and hydrotroilite (iron monosulfide FeS) is found in a subordinate amount.

In the sediments' material, pyrite is found in the form of very fine crystal particles and framboids. Crystal particles, alone or in aggregations, are a common form of inclusions in the sediments of peat deposits [3]. Their dimensions, as a rule, do not exceed several microns. With fairly high magnifications, they often display a regular cubic form; pyrite framboids in transparent sections have the form of black spherules, which are spherical aggregations of individual pyrite crystal particles in polished sections with magnification of 600 times. They are characterized by high reflectivity and have a golden-milky color. The dimensions of framboids vary in the range from 5 to 33 μ (average $\sim 10 \mu$). Their dimensions are usually tenths of a micron. In most cases, framboids in peat material and mineral sediments are found in aggregations, the composition of which may include tens of individual forms; less often, they form dispersed impregnation. Sometimes, the framboids in aggregations lie fairly tightly against each other and form microconcretions. Framboids and crystal particles of pyrite in the sediments of peat deposits are confined to gelled components, which are products of microbial decomposition of plant tissues. Pseudomorphs of pyrite on remains of the tissues of herbaceous and woody

TABLE 2. Contents of Total Iron in Peat-Forming Plants

Type of peat-forming plant	Morphological parts of the plant	Ash content, A ^c , %	Fe _{tot} , % of air-dry matter	Corg, %
Reed	Plant as a whole	7,93	2,57	43,50
	Rhizome	11,38	5,56	42,13
	Leaves	7,55	0,78	44,42
	Stems	4,87	1,38	43,94
Sedge	Rootlets	2,27	2,32	46,42
	Vegetative organs	1,88	1,59	46,50
Alder	Trunks	1,97	2,60	48,50
Sphagnum	Plant as a whole	4,84	3,53	42,56
Rush	The same	1,85	2,49	46,94

plants are frequently found, and also pseudomorphs of pyrite on diatoms in lake sediments and on foraminifers in deposits of coastal zones of the sea. In plant tissues that have preserved their anatomical structure, pyrite is most often found in cell cavities, which indicates the use of readily assimilable intracellular organic matter by sulfate-reducing bacteria. In some cases, pyrite replaces starch grains in cellular structures. In their investigations, the authors paid attention to the fact that the morphology of pyrite inclusions in the sediments of peat deposits in the Colchian lowland duplicates the morphological forms of inclusions that are found in coal seams of deposits of various ages. This indicates that processes of sulfide formation and the factors causing it are fairly similar in contemporary, as well as in ancient peat bogs.

The second form of sulfide mineralization of iron, hydrotroilite FeS, was discovered in sediment of the upper layer of Lake Paliastomi represented by silty clay. Hydrotroilite colors the clay sediment black. However, in air the black coloring disappears, and the sediment acquires the gray color characteristic of clay, with brown spots and fields of iron hydroxides, due to oxidation of hydrotroilite. As is known [1, 4, 5, etc.], hydrotroilite is the primary product of interaction of hydrogen sulfide and iron, which is transformed into pyrite in the course of diagenesis, as a consequence of dehydration and the addition of free sulfur in the reaction $\text{FeS} + \text{S} = \text{FeS}_2$ [4, 8]. This indicates that the hydrotroilite in lakes connected with regions of peat accumulation in Belorus is a basic component of surface littoral sands and pelagic clays: they indicate that hydrotroilite accounts for ~50% of the total sulfur in such sediments. Since hydrotroilite is only found in upper layers of lake sediments, and further down through the cross section it is not found, we can suppose that it is a metastable phase in the process of formation of pyrite. Among the material of genetic types of sediments of peats and peaty clays composing peat deposits of Colchis, inclusions of hydrotroilite are not macroscopically distinguishable in visible form.

DISTRIBUTION OF IRON SULFIDES IN CROSS SECTIONS AND OVER THE AREA OF PEAT DEPOSITS OF COLCHIS

Since we only noted the hydrotroilite form of sulfide mineralization in surface clay sediment of Lake Paliastomi and did not find it in peat deposits studied in field conditions, in this section we will only talk about pyrite.

The pyrite content in genetic types of sediments in the peat deposits that were studied varies in a wide range: from <1 to >5%,* figured in relation to dry matter (Fig. 1). As observations under a microscope show, pyrite is extremely unevenly distributed in the cross section of peat deposits, forming layers with different concentrations. In the distribution of little layers with maximum and minimum concentrations of pyrite through the cross section, a definite confinement to corresponding genetic types of sediments arranged in different parts of them is observed. In most of the cross sections, alternation, as it were, of increased and reduced contents of it is noted. This can be graphically illustrated on the example of borehole 202 in the Anaklia deposit [7] and many others. But there are cases (Moltakva deposit) when the genetic types of sediments with the greatest concentration of pyrite definitely gravitate to the upper half of the peat bed [7]. In borehole 105 in the Imnat deposit, the genetic types of sediments with increased pyrite concentration, on the contrary, are more characteristic of the lower half of the peat deposit's cross section, and in the Ochamchir deposit (borehole 501) the

*The volume content of pyrite was determined by the point method in polished sections and sections made from sediment samples.

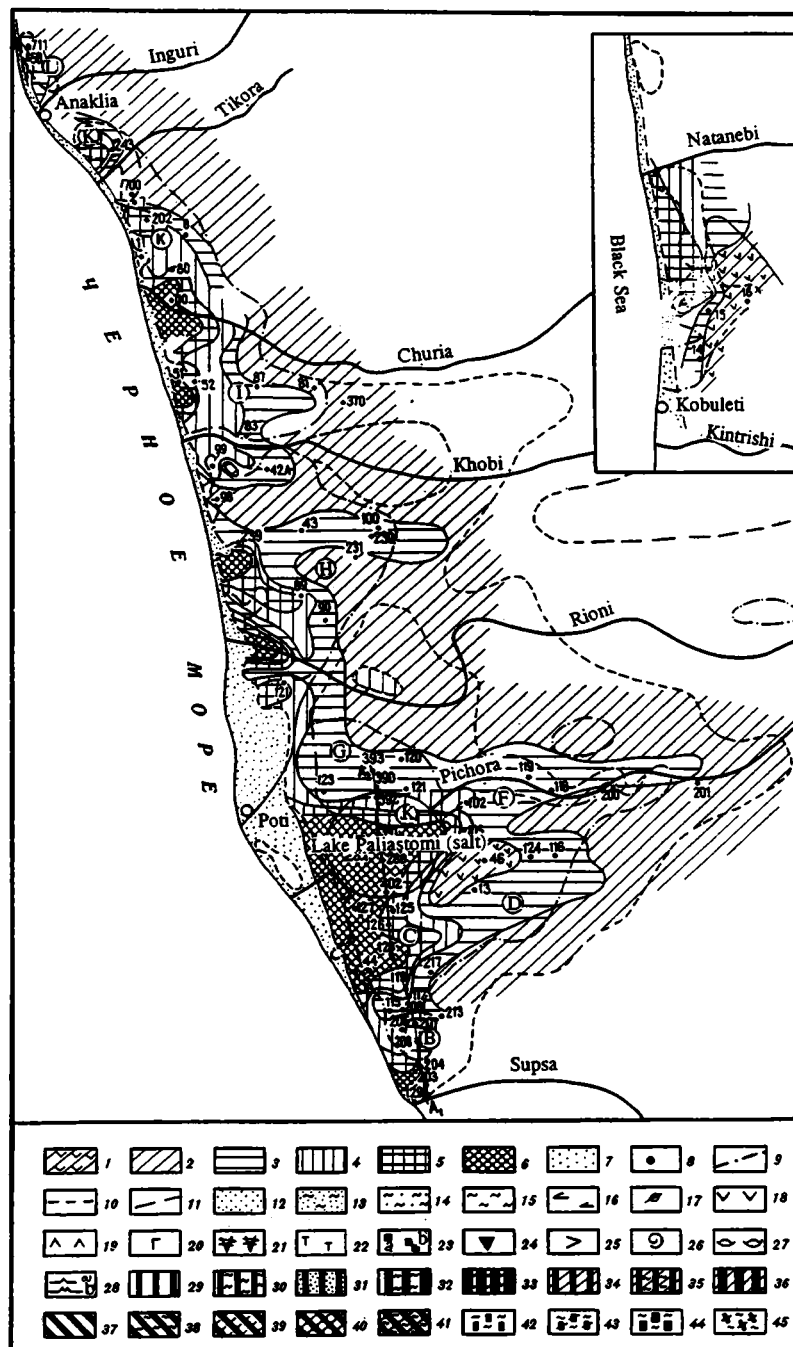
TABLE 3. Form of Iron in Sediments of Peat Deposits in the Abkhazian-Megrel and Poti Basins of the Colchian Lowland

Number of borehole (in numerator), number of specimen (in denominator)	Depth, m	Genetic type of sediment	In % of dry residue						In % of reactive iron			C _{org} , %	pH
			Fe _{tot}	Fe _{ina}	Fe _{reac}	Fe ³⁺	Fe ²⁺	Fe _{pyr}	Fe ³⁺ HCl	Fe ²⁺ HCl	Fe _{pyr}		
Zorgat deposit													
$\frac{58}{783}$	1,50	Fine-grained silt with woody attritus	5,02	1,36	3,66	2,01	1,45	0,20	55,0	39,6	5,5	—	6,9
$\frac{58}{787}$	2,50	Fine-grained silt with a large amount of woody remains	4,83	1,30	3,53	1,39	2,07	0,07	39,4	58,6	2,0	—	5,8
$\frac{58}{790}$	3,75	Clay with woody remains, carbonate	6,20	1,81	4,39	2,63	1,67	0,09	60,0	38,1	2,0	—	7,8
$\frac{58}{794}$	4,75	The same	5,59	2,32	3,47	1,92	1,45	0,11	55,2	41,6	3,2	—	7,7
Anaklia deposit													
$\frac{7}{128}$	1,00	"	4,15	1,80	2,35	1,34	0,89	0,12	57,0	37,9	5,1	3,73	7,6
$\frac{7}{130}$	1,50	Fine-grained silt with humus (subsoil)	6,11	1,56	4,55	2,63	1,84	0,08	57,8	40,5	1,7	—	6,5
$\frac{7}{133}$	2,15	Clay with woody remains, attritus, and humus	4,42	1,78	2,64	1,01	1,56	0,07	38,3	59,1	2,6	2,96	6,5
$\frac{7}{135}$	2,75	Fine-grained silt with woody attritus, humus, and rootlets (soil)	5,04	1,73	3,31	1,08	1,95	0,08	36,8	60,7	2,5	—	—
$\frac{7}{137}$	3,25	Fine-grained silt with humus, carbonate	5,19	1,85	3,34	1,01	2,23	0,10	30,2	66,7	3,0	—	7,6
Nabad deposit													
$\frac{12}{218}$	0,25	Clay with woody, gelinite-precollinite peat (slightly peaty)	3,49	1,58	1,91	0,45	1,43	0,03	23,6	75,0	1,6	20,52	4,95
$\frac{12}{220}$	0,65	Fine-grained silt with woody, gelinite-precollinite peat (slightly peaty)	3,70	1,89	1,81	0,70	1,09	0,02	38,6	60,2	1,0	15,24	4,85

<u>12</u> 225	1,75	Fine-grained silt with woody attritus	5,94	1,06	4,88	3,43	1,43	0,02	70,3	29,3	0,4	1,49	7,30
<u>12</u> 229	2,75	Fine-grained silt with woody attritus and rootlets, carbonate (soil)	4,53	1,50	3,03	1,28	1,62	0,13	42,3	53,5	4,3	3,37	7,35
<u>12</u> 232	3,75	Coarse-grained silt with woody attritus, carbonate	4,99	1,62	3,37	1,78	1,51	0,08	52,2	44,8	2,4	2,69	7,40
<u>12</u> 234	4,25	Clay with woody, gelinite-precollinite peat (slightly peaty)	4,45	1,89	2,56	0,62	1,84	0,10	24,1	71,9	3,9	19,3	5,05

Innat deposit

<u>45</u> 667	0,50	Clay with lumpy structure, woody attritus, rootlets, and diatoms (contemporary soil)	4,71	2,40	2,31	1,73	0,56	0,02	74,9	24,2	0,9	12,48	5,20
<u>45</u> 668	1,00	Clay with woody attritus and root remains (contemporary subsoil)	3,49	1,90	1,59	1,06	0,50	0,03	66,6	31,4	1,9	16,90	5,40
<u>45</u> 677	4,00	Clay with woody, gelinite-precollinite peat (slightly peaty)	4,10	1,24	2,86	0,83	2,01	0,02	29,0	70,3	0,7	23,18	5,20
<u>45</u> 680	5,25	Clay with woody attritus and stem remains, carbonate	4,63	1,45	3,18	1,57	1,56	0,05	49,4	49,1	1,6	1,66	7,8
<u>45</u> 684	6,50	The same	4,47	1,17	3,30	1,73	1,51	0,06	52,4	45,7	1,8	1,66	8,0



genetic types of sediments with increased pyrite content are concentrated in the upper and lower parts of the peat bed. In many cross sections of peat deposits, the distribution of pyrite corresponds fairly well to the distribution of sulfate-reducing bacteria (borehole 202 of the Anaklia deposit, 217 of the Grigoleti deposit, 501 of the Ochamchir deposit), which indicates a close interrelation of processes of sulfide formation in peat deposits with the vital activity of these bacteria [7]. At the same time, there are cases of the absence of a direct correlation of pyrite and sulfate-reducing bacteria in individual parts of the cross sections of peat deposits, and lack of correspondence is also found in the quantitative ratio of the two, although the distribution curves are similar to each other in configuration [7]. These cases are entirely explainable. As is known, sulfate-reducing bacteria are the main generator of hydrogen sulfide in early diagenesis. However, the ecological range of conditions in which vigorous activity of these microorganisms is possible [2] is significantly wider (in pH-Eh coordinates) than the zone of thermodynamic stability of hydrogen sulfide. All of this leads to a situation in which biogenic hydrogen sulfide can be partially or completely oxidized and thus eliminated from the process of sulfide mineral formation [8].

Fig. 1. Distribution of zones of sulfide mineralization (pyrite) in the region of peat accumulation in the Colchian lowland. 1) zero zone – absence of sulfide mineralization – sphagnum raised bogs; 2) first zone of sulfide mineralization (S < 0.3%, pyrite 0.0); 3) second zone of sulfide mineralization (S 0.3-0.5%, pyrite < 1%); 4) third zone of sulfide mineralization (0.5-1.2%, pyrite 1-3%); 5) fourth zone of sulfide mineralization (S 1.2-2.2%, pyrite 3-5%); 6) fifth zone of sulfide mineralization (S > 2.2%, pyrite > 5%); 7) coastal bar; 8) boreholes and their numbers; 9-11) contours of peat bogs (9 – emerging to the surface, 10 – covered by younger terrigenous-clay sediments and buried to a depth of 25 m, 11 – supposed buried ones); 12) fine-grained sand; 13-14) silt (13 – coarse-grained, 14 – fine-grained); 15) clay; 16) stem remains; 17) remains of leaves; 18-19) attritus (18 – woody, 19 – herbaceous); 20) gelated colloidal matter; 21) plant rootlets; 22) soil formations; 23) pyrite (a – a little, b – a lot); 24) iron hydroxides; 25) sponge spicules; 26) foraminifers; 27) freshwater fauna; 28) diatoms (a – a little, b – a lot); 29) woody gelinite-precollinite peat; 30) woody gelinite-precollinite clayey peat; 31) woody gelinite-precollinite peat with sand; 32) woody gelinite-posttelinite clayey peat; 33) woody gelinite-telinite clayey peat; 34) woody-sedge gelinite-precollinite peat; 35) woody-sedge gelinite-precollinite clayey peat; 36) woody-sedge gelinite-posttelinite peat; 37) reed gelinite-precollinite peat; 38) reed gelinite-precollinite clayey peat; 39) sedge-reed gelinite-precollinite washed peat; 40) sedge-reed gelinite-precollinite peat; 41) sedge-reed gelinite-precollinite clayey peat; 42) clay with woody gelinite-precollinite peat; 43) clay with woody-sedge gelinite-precollinite peat; 44) clay with woody gelinite-posttelinite peat; 45) clay with sedge-reed gelinite-precollinite peat. *Peat deposits*: A) Kobuleti, B) Grigoleti, C) Moltakva, D) Imnat, E) Paliastomi, F) Pichora, G) Poti, H) Nabad, I) Churia, J) Anaklia, K) Tikora, L) Zorget.

Comparative evaluation of the degree of sulfide mineralization of cross sections of peat deposits as a whole enabled us to establish zones in the area of peat accumulation in the Colchian lowland that are characterized by certain limits of variation in the contents of sulfur and iron sulfides in them (Table 4). Quantitative evaluation of the zones' degree of sulfide mineralization was the result of calculations of the average contents of sulfur and pyrite that were carried out for 150 cross sections of peat deposits. In cases of clear delineation of the lower and upper parts of the deposits with respect to pyrite and sulfur content, both were calculated separately for each part of the deposit's cross section.

As we can see from Table 4, six zones of sulfide mineralization of peat deposits in Colchis were distinguished, including one without pyrite; the zones' areal distribution and relationship are shown on the map (see Fig. 1) and illustrated by the profile (see Fig. 2). From analysis of the profile, it follows that, in some cases, the type of sulfide mineralization of a peat deposit does not change in the whole history of accumulation of its sediments in time (boreholes 129-128 inclusive and 392 and 393). In other boreholes, as, for example, in the region of Lake Paliastomi (boreholes 402, 288, and 391), the second type of zone of sulfide mineralization, which is confined to the lower part of the peat deposit, is replaced by the fifth type in its upper part, represented by the lake deposits of Paliastomi. In the profile, we can also see the nature of succession of one type of zone of sulfide mineralization of a peat deposit by another, which is gradual in most cases. The zones of sulfide mineralization that were distinguished are easily seen on a map (see Fig. 1). Their distribution in the overall landscape plan of the coastal region of peat accumulation in Colchis is governed by certain patterns. The zones of types IV and V of sulfide mineralization of peat deposits are connected with the coastal strip of the region of peat accumulation and gravitate to the mouths of large rivers of the Colchian lowland plain and to the shores of lakes that have a link with the waters of the Black Sea (the southern and central parts of Lake Paliastomi). The zones of types II and II, with less sulfide mineralization, as a rule, are characteristic of more remote parts of the region of peat accumulation of the Black Sea and the marginal strip adjacent to uplands. The zone of type I, with low sulfide mineralization, is also characteristic of the peat deposit of the northernmost zone of Lake Paliastomi and the adjacent shore.

The zone of type 0, in which sulfide mineralization is practically absent, is localized in the upper part of the cross section of sphagnum peat bogs of the Imnat and Kobuleti deposits. The lower horizons of these peat bogs belong to the lowland type and are characterized by more intensive sulfide mineralization (see Fig. 1). Our attention is drawn to the fact of lower sulfide mineralization of the lowland Kobuleti peat bog, in spite of its location in the coastal zone of the Black Sea. The average sulfide contents within the bounds of zones III and IV distinguished here are close to the low values of

*The volume content of pyrite was determined by the point method in polished sections and sections made from sediment samples.

TABLE 4. Average Contents of Pyrite and Sulfur in Different Zones of Sulfide Mineralization of Peat Deposits in Colchis

Type of zone of sulfide mineralization	Average sulfur contents in relation to dry matter, %	Average pyrite contents in relation to dry matter, %
0	0,0	0,0
I	< 0,3	0,0
II	0,3—0,5	< 1
III	0,5—1,2	1—3
IV	1,2—2,2	3—5
V	> 2,2	> 5

the corresponding intervals (see Table 4). This peculiarity of the Kobuleti peat bog is explained by its location against the background of raised relief of the Kobuleti basin, in the sphere of weakened action of sulfate-containing seawaters. As was shown previously, the rivers of this trough (Natanebi, Kintrishi, Choloki) contain very little sulfate ions near their mouths. The zonality of sulfate mineralization of peat bogs in the Colchian lowland that was shown completely agrees with the distribution of sulfur concentrations in them, which, as was shown previously, entered the sedimentation basin in the composition of sulfate ions in Black Sea water.

One of the interesting facts discovered in analyzing the areal and stratigraphic patterns of sulfide distribution is connected with the region of Lake Paliastomi. Previously, we paid attention to the low concentration of sulfides in peat lying at the base of the bay's deposits and, on the other hand, the high sulfide content in the latter (see Fig. 1).

In evaluating this fact, we have to come to the conclusion that flooding, about 3000 years ago, of part of the peat area with salt waters of Paliastomi (content of sulfate ions more than 600 mg/liter) did not have a noticeable effect on the sulfide content in buried peat.*

Having considered features of the spatial distribution of sulfide mineralization in the region of peat accumulation of the Rioni intermontane trough as a whole, we can establish the regional confinement of zones of high concentration of iron sulfides (and sulfur) to the coastal region of peat accumulation, with the width of these zones being maximum near the mouths of rivers in the central part of the trough and decreasing toward its edges.

Thus, increased sulfide mineralization is a characteristic feature of the coastal-continental type of peat accumulation and, in connection with this, is areally distributed in accordance with the overall landscape and geochemical zonality of the Rioni intermontane trough.

Fixing the connection of sulfide formation with the coastal-continental type of peat accumulation, we can state its complete analogy with processes of ancient peat accumulation (coal formation). Enrichment with iron sulfides (high sulfur content) is a common property of coastal-continental peat bogs (coal seams of the Donets, Podmoskovnyi, L'vov-Volyn, Kizelov, Pichora, and other coal basins). Consistent manifestation of the corresponding pattern in the geological history of peat accumulation and coal formation makes it possible to use the data obtained to solve many critical scientific and practical problems of coal geology, for example, in reconstructing the conditions of ancient peat accumulation and developing methods of predicting the quality of coal seams

The investigations that were conducted make it possible to evaluate a complex set of factors interacting in the process of accumulation of sulfur and sulfides in peat bogs.

The concentration of sulfates in the waters feeding peat bogs, and the presence of a certain amount of organic matter accessible for assimilation by sulfate-reducing bacteria are of decisive significance. The combination of these factors forms a general pattern: the peat bogs with the most sulfur and most enriched with sulfides are located in the coastal-continental zone, on depressed areas near the mouths of rivers, where the effect of seawaters enriched with sulfates is more frequent and prolonged.

The entry of sulfates into the Colchian peat basin in the composition of seawaters determines the basic spatial pattern of distribution of sulfides, which is connected with the corresponding genetic types of sediments and their facial affiliation in the overall landscape plan of the region of peat accumulation in the Colchian lowland.

*We will note that the base of the peat deposit under the sediments of Paliastomi is synchronous (6000 years) with the beginning of contemporary peat accumulation in Colchis. This indicates that the Paliastomi lagoon is not a relict of the Colchian Bay, but originated considerably later (about 3000-4000 years ago, according to data on the absolute age of upper layers of peat buried under bottom sediments).

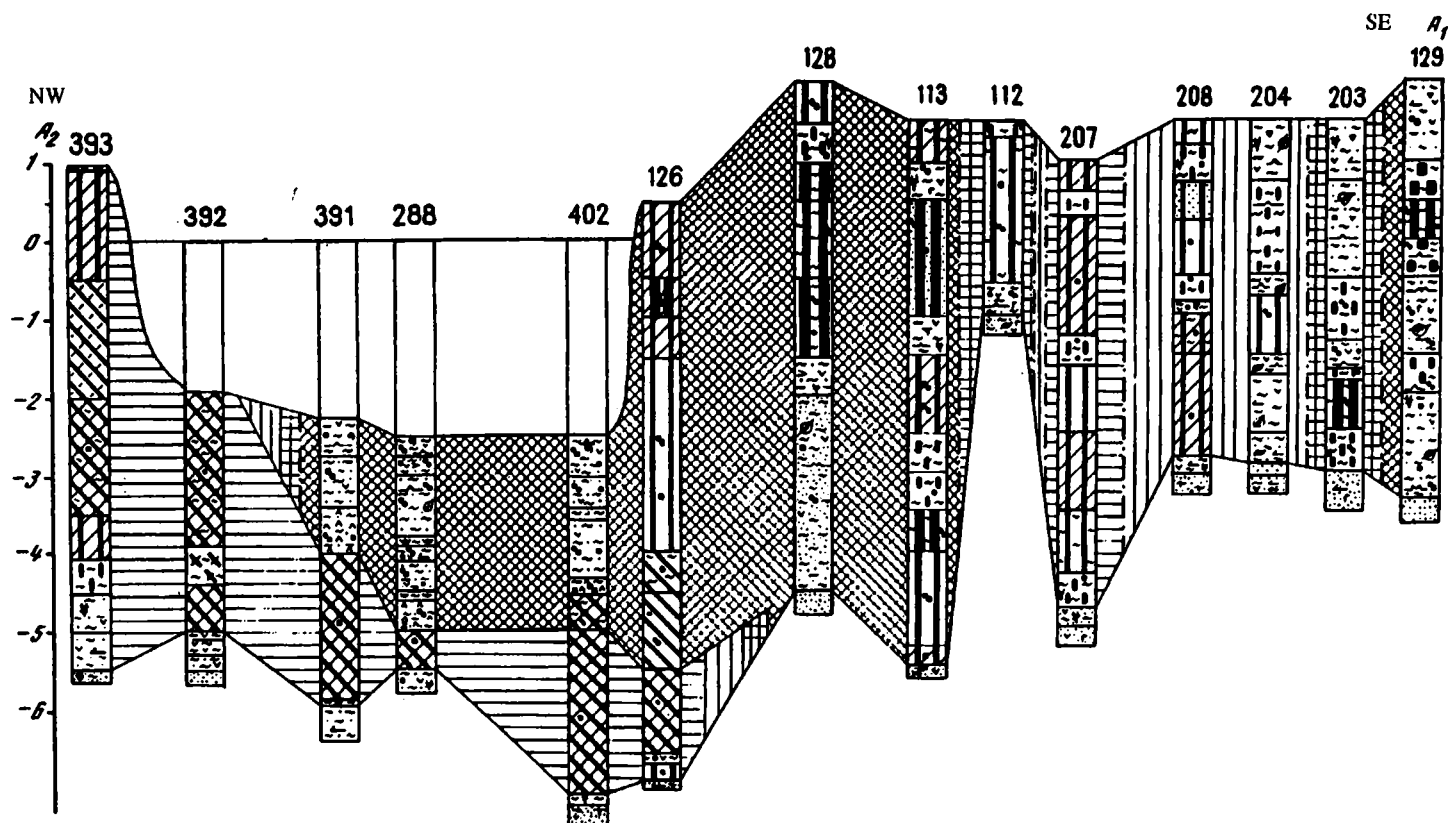


Fig. 2. Schematic profile (A₁ – A₂) of the distribution of zones of sulfide mineralization of the Moltakva and Grigoleti peat deposits. See Fig. 1 for conventional notations.

A clear similarity is displayed between the nature of sulfide mineralization of peat bogs and coal seams. This is primarily true of the increased concentration of sulfides in coastal parts of contemporary and ancient peat areas, the mineral composition of sulfides, their morphology, and complex, layered distribution in the cross sections of peat bogs. Thus, we can note the genetic unity of processes of sedimentation and sulfide mineral formation in contemporary and ancient peat bogs.

The new data cited in the present work on sulfides and sulfur in peat deposits of the Colchian lowland fill a significant gap in the geochemistry of early diagenesis of mineral sediments and organic matter, and they are also a definite contribution to the theory of the sedimentary process as a whole and to certain critical problems of coal geology, in particular.

LITERATURE CITED

1. A. D. Arkhangel'skii, "Ferrous sulfide in deposits of the Black Sea," BMOIP, No. 12 (3), 431-441 (1934).
2. L. G. Baas-Beking, I. R. Kaplan, and D. Moore, "Limits of variations in pH and oxidation-reduction potential of natural media," in: Geochemistry of Lithogenesis [Russian translation], Izd-vo Inostr. Lit., Moscow (1963), pp. 11-84.
3. L. Ya. Kizil'shtein, Genesis of Sulfur in Coals [in Russian], Izd-vo Rostov. Un-ta, Rostov-na-Donu (1975).
4. K. I. Lukashev, V. A. Kovalev, A. L. Zhukhovitskaya, et al., "Forms and dynamics of sulfur in peats and sediments of lakes in Belorussia," Litol. Polezn. Iskop., No. 3, 34-47 (1972).
5. N. M. Strakhov, "Sedimentation in the Black Sea," in: Formation of Sediments in Contemporary Bodies of Water [in Russian], Izd-vo AN SSSR, Moscow (1954), pp. 81-136.
6. N. M. Strakhov, Forms of Iron and Their Significance for the Theory of Diagenesis. Understanding the Diagenesis of Sediments [in Russian], Izd-vo AN SSSR, Moscow (1959), pp. 92-119.
7. P. P. Timofeev, L. I. Bogolyubova, and L. Ya. Kizil'shtein, "Sulfide formation in the region of contemporary peat accumulation of the Rioni intermontane trough. Communication 1," Litol. Polezn. Iskop., No. 1, 3-28 (1994).
8. F. V. Chukhrov, "Pyrrhotine and pyrite in kerogen ores and some general questions of the genesis of iron sulfides," Izv. AN SSSR, Ser. Geol., No. 1, 129-154 (1936).

SEDIMENTS OF THE CONTEMPORARY DRIED-UP BOTTOM OF THE ARAL SEA, THEIR DIAGENESIS AND EFFECT ON THE ECOLOGY OF THE ARAL REGION

I. V. Rubanov

UDC 551.577:552.14(575.172)

Lithological characteristics are given for subaqueous sediments of the contemporary dried-up bottom of the Aral Sea that were accumulated before the reduction in its level. It was shown that after the sea's regression, caused by the anthropogenic factor, on the dried-up sea bottom sedimentogenesis exists only on a small scale in subaerial conditions. Diagenetic processes in the sediments acquire a noticeable role at this time. Deterioration of the ecological condition in the Aral region is determined not so much by removal of salts from the dried-up bottom as degradation of the plant cover and fauna, and especially by the inflow there of river waters known to be unsuitable for drinking.

The catastrophic reduction in level of the Aral Sea (by 15 m), which began in 1961 and was caused by a reduction in the inflow of water into it, has led to drying-up of bottom sediments on almost half of the sea's former area [22]. The reduction in waters of the Amu Darya and Syr Darya flowing into the Aral region has worsened their quality. The water in these rivers has not only become many times more salty (from 0.4 to 2 g/liter), but is also significantly poisoned with various toxic chemicals and fertilizers that come with discharge waters from irrigated lands in the catchment basin [4, 5, 11]. In a short time, the sedimentary material previously accumulated in a water (subaqueous) environment has emerged from under the sea level and is now in subaerial conditions, which has led to significant transformations in the exposed ground. Such a grandiose scale of disruption of the natural equilibrium under the action of the anthropogenic factor is a unique phenomenon in the history of the Earth. Therefore, it is of theoretical and practical importance to know peculiarities of the sediments' structure, their diagenesis (transformation) in conditions of the dried-up bottom, and also their effect on the surrounding environment (ecology).

Many researchers have analyzed peculiarities of the transformation of sediments of a subaqueous environment when they are converted to a subaerial environment [12, 21, 24, 28, 29, etc.]. P. P. Timofeev et al. [25] called this process *soil diagenesis*. We arbitrarily call it *diagenesis*.

Bottom sediments of the Aral Sea have been characterized in the works of many researchers [1, 2, 5, 9, 16, 17, 20, 23, 27, etc.]. Information about the structure and composition of the sediments was previously based exclusively on analysis of samples taken on board ships with dredges and coring tubes of various designs (straight-through, piston, vibrating-piston). The sampling points were separated from each other by distances of many kilometers (from 5 to 50 km). As a consequence of this, the reliability of data on the boundaries of change in lithological types of sediments laterally, the total amount of them, textural characteristics, etc. was insufficient. This is especially true of the Eastern Aral shallow water, with bays reaching deeply into the continent, and the Akpetki archipelago, where ships could not go to take samples.

Study of sediments of the dried-up bottom was carried out by itinerant traverses (on foot, and by automobile, helicopter, and airplane) of its main landscape and lithological varieties, using satellite and aerial photographs. Samples were taken directly from the surface of the sediments, as well as in test pits and holes bored with a motorized auger (to a depth of as much as 3-5 m). Sampling was done at more than 300 observation points separated from each other by a distance (2-50 km) sufficient to trace the boundaries of adjacent lithological units.

As the sea level dropped, it became possible to study directly bottom sediments that had previously been concealed under water. This not only made it possible to clarify their structure, but also to reveal previously unknown lithological types of sediments. Thus, along the former shallows, for the first time we distinguished two extensive zones of chemogenic sediments: carbonate and gypsum [16-18]; and in the Akpetki archipelago we established a new type of organogenic sediments for the Aral Sea: sapropellike [18].

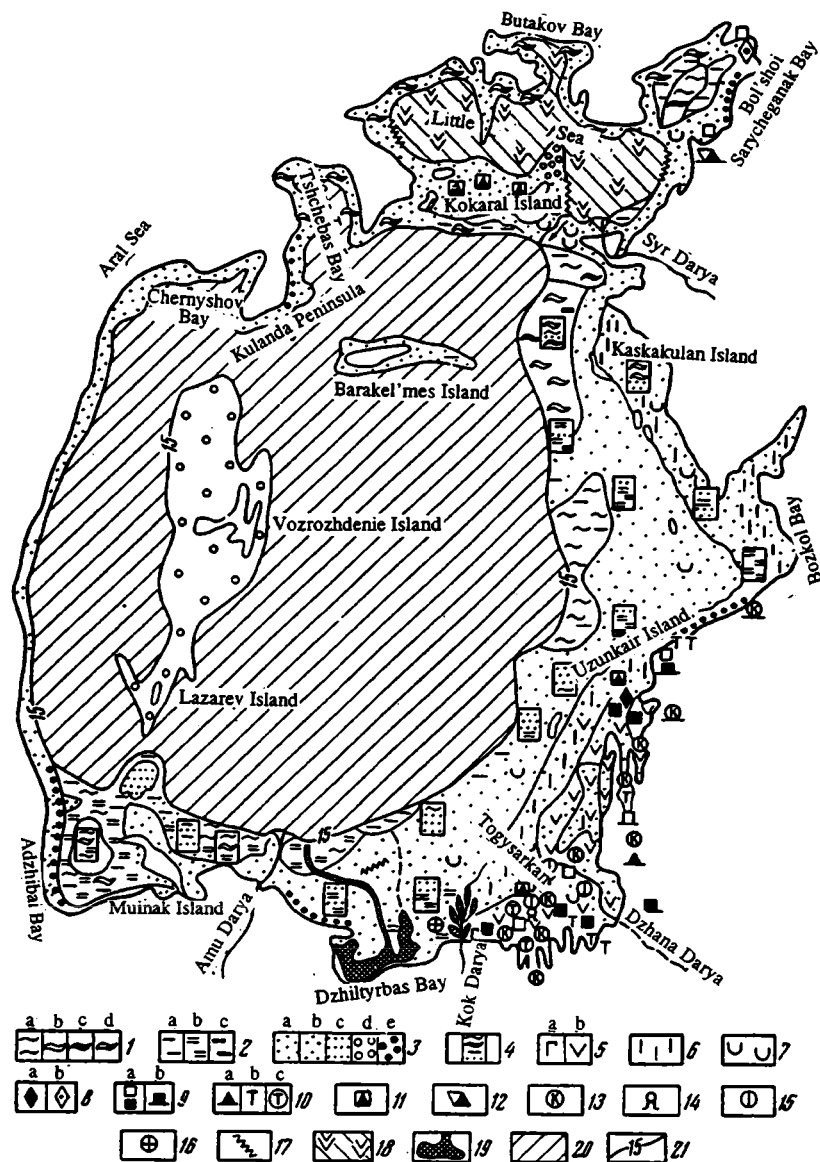


Fig. 1. Diagram of the lithology of surface sediments of the contemporary dried-up bottom of the Aral Sea (subaqueous stage) to a depth of 1 m (on January 1, 1991): 1) clay (a - marine gray, b - delta brown, chocolate, c - bog dark, black, d - montmorillonite green); 2) silt (a - marine light, b - delta brown, chocolate, c - bog dark); 3) sands (a - polymictic brownish, b - clastic-carbonate rust-colored, c - quartz light, of Cretaceous age, d - oolitic light, e - dune); 4) succession of lithological varieties of sediments to a depth of 1 m; 5) gypsum (a - gypsum crusts and thin layers on dried-up soils, b - gypsum dust and sand of the gypsum zone, composed of light crystals with an irregular shape, 0.01-1 mm); 6) carbonate dust of the carbonate zone as an admixture to terrigenous sediment; 7) mollusc shells; 8-12) chemogenic sediments, part of which accumulated after formation of the contemporary dried-up bottom, and part in ancient times: 8) mirabilite on the dried-up bottom (a - on the surface, b - buried), 9) halite (a - on the contemporary dried-up bottom, b - the same on the ancient Aral terrace; light symbol - thickness from 5 to 20 cm, dark - from 20 to 150 cm), 10) thenardite (a - crystalline, b - flaky, c - sulfates - thenardite flakes on top, crystalline mirabilite underneath), 11) halite underlaid by astrakhanite, 12) astrakhanite with thenardite; 13) kerchevniks; 14) stubble of gypsified reed; 15) sapropellike sediments; 16) peat; 17) the most significant accumulations of dead algae (chalan); 18) contemporary accumulation of gypsum in the Little Sea and Butakov Bay; 19) ponds of discharge (drainage) waters on the dried-up sea bottom; 20) aquatory of the Big Sea (salinity about 30 g/liter); 21) shoreline of the sea, the level of which has dropped by 15 m so far.

It is known that, before the reduction in its level, the slightly mineralized water (9-10 g/liter) of the Aral Sea was mostly in the carbonate stage of chemogenic sediment accumulation [2, 3]. Terrigenous sediment accumulation was predominant in the sea, while chemogenic (carbonate) sedimentation was noted primarily within the bounds of chalistic (far from shore) sections of the sea's aquatory (underwater territory). There, carbonate material accounted for as much as 50% of the total mass of sediments, and it was essentially marl [2, 5, 27].

The next zone of relatively more intensive chemogenic sediment accumulation, as we will see below, was located along the eastern, shallow-water shores of the Aral Sea, primarily within the bounds of the transisland zone and near the Akpetki archipelago.

At present, the salinity of seawater in the residual Aral Sea has increased sharply (from 10.2 to 36.2 g/liter), due to the reduction in water entering it and continuing intensification of its evaporation. This has led to the replacement of carbonate chemogenic sedimentation by sulfate (calcite by gypsum). Terrigenous sediment accumulation has decreased sharply as a result of the almost complete cessation of inflow of river waters into the sea (in individual years, no water at all comes from the Syr Darya and Amu Darya) and a decrease in shore abrasion (as a consequence of the lowering of sea level and flattening of the shores). On the former shallows that have emerged from under the sea level, normal marine sediment accumulation has practically completely ceased, and on the dried-up bottom that has formed new geological processes have developed, which are characteristic of the aerial conditions of a desert.

On the whole, the sediments of the contemporary dried-up bottom can be subdivided into subaqueous ones, which were accumulated in the sea's transgressive stage (before the beginning of formation of the dried-up bottom), and subaerial ones, which have formed on the dried-up bottom since the sea's regression (after 1961).

SEDIMENTS OF THE DRIED-UP BOTTOM IN THE SUBAQUEOUS STAGE

Among the sediments of the dried up bottom accumulated in the transgressive (subaqueous)* stage of the Aral Sea (before 1961), the following formations are distinguished: clastic, chemogenic, and organogenic.

Figure 1 shows the main lithological varieties of surface sediments on the dried-up bottom, and in individual sections of it insets show their stratification to a depth of 1 m.

Clastic sediments amount to more than 90% of their total mass. They are composed of sands, silts, and, less often, clays.

Sands are primarily quartz-feldspar, quartz, oolitic, and, at the Ustyurt scarp, calcareous-clastic. Within the bounds of the contemporary dried-up bottom, sands account for about 80% of its sediments. Sands almost uninterruptedly circle the residual Aral Sea and its islands, being the sediments of the wave-cut facial zone there (belt according to V. I. Popov) [13]. Only within the bounds of the contemporary and ancient deltas of the Amu Darya and Syr Darya (on the south and east sides of the Aral Sea) is sandy material facially replaced by silts; in the north (in the Little Sea), along bedrock outcrops of Paleogene clays, the sandy dried-up bottom is replaced primarily by clay. Quartz-feldspar sands mostly make up the southern and eastern dried-up bottom; calcareous-clastic, the western one; and quartz sands, small sections in the regions of outcrop of Cretaceous and Paleogene sands in the east and at the Ustyurt scarp, and also at Druzhba Island (in the southwestern part of the Aral Sea). Oolitic sands are found primarily around Lazarev and Vozrozhdenie Islands.

Silts amount to approximately 15% of the mass of sediments and are found mostly near the contemporary and ancient deltas of the Amu Darya (in the south and southeastern parts of the Aral Sea) and Syr Darya (in the east), mostly constituting the sediments of floodplain facies of the abovewater deltas and alluvial-marine sediments of the underwater deltas. Besides that, significant sections of silty sediments of the dried-up bottom have begun to be exposed (following sands) in the coastal zone of the shrinking Aral Sea. The silts' mineral composition is mostly polymictic.

Clays on the dried-up bottom have their maximum extent along the northwestern shores of the Little Sea, where they make up sediments of the wave-cut facial zone. They form there as a result of erosion of bedrock outcrops of Paleogene hydromica and montmorillonite clays.

*Minor fluctuations (± 3.5 m) in the sea's level were observed over the course of the last few centuries. Here, by transgression we mean an excess of the sea's level above absolute elevations from +45 to +53 m; and by regression, a drop in the sea's level below +45 m.

An increased amount of clay material is also noted within the bounds of small sections of the stagnant zone of the former underwater deltas of the Amu Darya and Syr Darya in the south and east of the dried-up sea bottom. In all, clay accounts for about 5% of the mass of sedimentary material on the dried-up bottom.

Chemogenic sediments that accumulated in the territory of the future dried-up bottom of the Aral Sea (before the beginning of reduction in its level, i.e., prior to 1961) are represented by calcium carbonate and sulfate (calcite, gypsum), and by water-soluble salts (mirabilite, thenardite, halite, astrakhanite). Carbonates, as we said before, accumulated over the whole aquatory of the Aral Sea, since it was in the carbonate stage of its salinization. Precipitation of carbonate from the seawater took place simultaneously with deposition of terrigenous material, and depending on the rate of deposition of the chemogenic or the terrigenous component of the sediment, their composition changed also. As a result, besides sediments enriched with carbonates in central sections of the sea (on account of the relatively slight conveyance of clastogenic material there), in the Eastern Aral shallow water (where there was more intensive evaporation of seawater heated all the way to the bottom and therefore more salty) carbonate sedimentation itself occurred more intensively, while terrigenous sedimentation was less intensive (since the wave movement there was weakened by the shallow water). This was also promoted by the presence, several tens of kilometers from the Eastern Aral shore, of a meridional chain of islands stretching parallel to the shore, which obstructed mixing of these waters with the waters of the open sea. All of this led to relative enrichment of the sediments with carbonates, which also enabled us [19] to distinguish a carbonate zone of the dried-up bottom there (see Fig. 1). In the sediments of this zone, which are primarily represented by sands, carbonate accounts for as much as 20-30% of the mass of sedimentary material.

Further to the southeast from this zone (even further from the open sea), carbonate chemogenic sedimentation was replaced by gypsum, which was almost not accompanied by deposition of terrigenous material. As a result, on individual areas of the southeastern dried-up bottom, the sea's former sandy bottom was covered with a sheet of chemogenic gypsum (crystals and aggregates of them) of sandy size, with a thickness of up to 20-30 cm. All of this enabled us to distinguish a gypsum zone there. In places, it reaches deeply into the continent, in accordance with the configuration of the former shallow-water bays that extended meridionally.

Gypsum not only settled freely on the sea bottom of these shallows, but also accumulated on the stems of plants growing in the Aral desert that was flooded in the last (prior to 1961) transgression of the Aral Sea. This led to the formation of distinctive gypsum mounds there – kerchevniki up to 1.5 m high and as much as 1.5-3 m in diameter.

Finally, in dead-end sections of narrow Eastern Aral bays, where the concentration of salts in the seawater reached 100 g or more, water-soluble salts (mirabilite-thenardite, halite, astrakhanite) were precipitated, which were preserved there in the form of small spots (halmeic sediments).

Organogenic formations that accumulated before the beginning of the reduction in level of the Aral Sea are the least common among sediments of the dried-up bottom, altogether amounting to no more than a few percent of their total mass. They are represented by shells and plant remains. Among the shells, most are of molluscs – *Cardium* (the size of which reaches 3-3.5 cm); fewer are of *Adacna*, *Dreissena*, and *Gidrobia* (up to 1 cm) and ostracods (up to 1 mm). Accumulations of shells sometimes form layers up to several tens of centimeters thick on an area of several hundred square meters.

Of plant remains, *Zostera* algae are predominant (their local name is "chalan"); they are found on the dried-up bottom in the form of ridges extending several hundred meters, with a width up to 20 m and thickness up to 1 m.

In individual sections of the former southeastern shallows (Akpetki), lenticular bodies of sapropel-like sediments are found (accumulations of semirotten plant remains and, in a lesser amount, shells of dead organisms), which accumulated on the bottom of small depressions (up to a few hundred meters in diameter and 2-3 m deep).

In their natural form, these sediments are unsteady, gelatinous, dark (rust-colored), organomineral matter (carbonate-clay, silty-sandy) with organic-carbon content up to 2.56%. There are also accumulations of peat-like material, which is the partially carbonized remains of reed thickets. It is mostly found west of the Akpetki archipelago, at the sea's former boundary with the shore, where "spots" form on the surface of the silty-sandy ground, with an area up to 100 × 100 m each and thickness up to 15 cm.

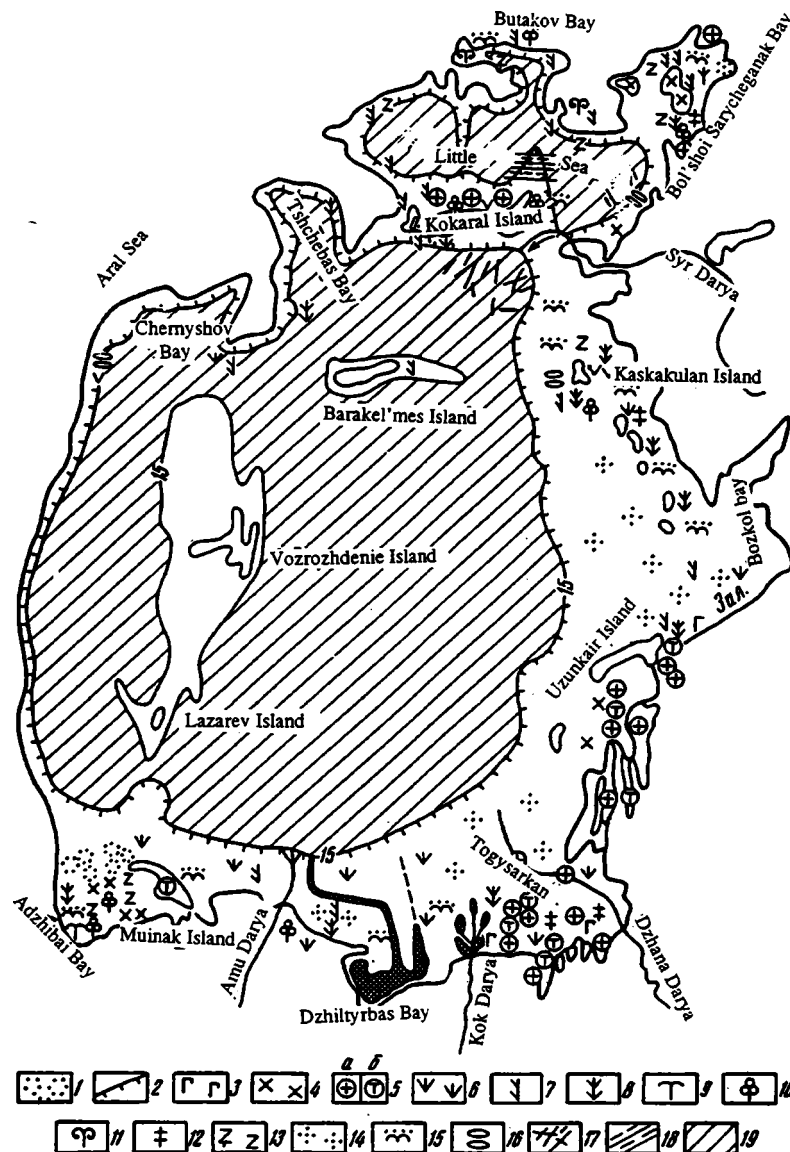


Fig. 2. Diagram of lithogenesis in the subaerial stage of the dried-up bottom of the Aral Sea (sedimentation and diagenesis). *Sediment accumulation*: 1) aeolian (wind-blown sands on bottom sediments); 2-5) chemogenic (including intrasoil salinization): 2) crust solonchaks of the marsh zone, 3) gypsum crusts and layers on dried-up soils, 4) solonchaks on the bottom of depressions, 5) accumulations of salts (a – halites, b – sulfates); 6-12) phytogenic (6 – *Salsola*, 7 – *Suaeda*, 8 – *Atriplex*, 9 – rush-reed, 10) tamarisk, 11 – forbs, 12 – saxaul). *Diagenesis* (including intrasoil salinization): 13) desiccation (shrinkage cracks); 14-15) deflation (14 – small barchans on sandy soils, 15 – barchans formed on account of bottom sediments of the sea's wave-cut zone); 16-18) erosion and other processes (16 – washouts on fine-grained bottom sediments – "sheepbacks," 17 – ship's-bottom furrows, mostly on the bottom of the contemporary sea, 18 – lineaments); 19) residual waters of the Little and Big Seas. See Fig. 1 for the rest of the notations.

Sediments of the Dried-Up Bottom in the Subaerial Stage

As bottom sediments of the Aral Sea emerge from under the sea level, the subaqueous environment of sediment accumulation in the shallow-water region is replaced by a subaerial environment. In this case, sedimentogenesis proper fades away to a significant extent, being replaced primarily by diagenesis. Sediment accumulation on the dried-up bot-

tom is reduced (Fig. 2) to aeolian (predominant), chemogenic (in a lesser amount), and phytogenic (insignificant). Chemogenic sedimentogenesis occurs on the dried-up bottom essentially in subaqueous conditions (in residual and seepage bodies of water on the surface).

Aeolian sedimentogenesis is occurring most intensively in the northern part of the former Adzhibai Bay. There, wind-blown masses of sandy material formed as a consequence of deflation of coastal sediments in front of the scarp and sediments in the region of the Tiger's Tail on the former Muinak Island. Moving toward each other under the action of the wind, they joined together, covering fine-grained (clay-silt) marine bottom sediments with aeolian sands. The thickness of these aeolian sediments (collected in barchans and in horizontal beds of sand) reaches 1-3 m. Covering the flat surface of the bay's marine sediments, the sands simultaneously fill deep (as much as 1.5 m) cracks (up to 20 cm wide). The latter form due to desiccation of the fine-grained material. The rock formed in this way combines sediments of subaqueous and subaerial genesis. One of the varieties of sandy diapirism mentioned in the literature [26] is probably created in this way in nature. Large sand masses were formed as a result of aeolian movement (sediment accumulation) on the Eastern Aral dried-up bottom (especially south of the mouth of the Syr Darya); less significant ones, in the northeastern part of Bol'shoi Sarycheganak Bay, and also in the eastern part of Kokaral and Barsakel'mes Islands.

Chemogenic sediment accumulation is occurring on the dried-up bottom in subaqueous, as well as in subaerial conditions. Subaqueous chemogenic sedimentogenesis is primarily reduced to precipitation of salts from salinizing residual seawaters and groundwaters feeding salt lakes (after the sea receded) — carbonates, gypsum, and water-soluble salts. Authigenic carbonates and gypsums do not collect in any noticeable monomineral sheets, while water-soluble salts form independent layers with an area up to several square kilometers (for example, the salt lake on the dried-up bottom north of Kokaral Island, with an area of about 10 km²), with a thickness of several tens of centimeters. In the mineral composition of water-soluble salts (halmeic sediments), halite, mirabilite (thenardite), and astrakhanite are predominant, less often glauberite and epsomite.

The most significant subaqueous chemogenic sediment accumulation is noted in the southeastern part of the dried-up bottom of the Aral Sea (in the Akpetki archipelago) and on the dried-up bottom north of Kokaral Island. In the Akpetki, numerous mirabilite-thenardite salt beds, each about 100 × 100 m in size (with a thickness up to 30-50 cm), are confined to flat depressions located on gentle slopes, while halite-astrakhanite ones are confined to the bottoms of paleochannels of the Dzhana Darya (Togysarkan), where the thickness of salt lenses reaches 1 m; and their area, 50 × 100 m. On the dried-up bottom north of Kokaral Island, halmeic sediments are represented by three salt beds of halite-astrakhanite composition, with an area from 1 to 10 km² each.

Subaerial chemogenic sedimentogenesis is manifested on the dried-up bottom in the form of solonchaks, which are widespread within the bounds of the marsh zone of the shrinking Aral Sea and on depressed sections of the rest of its territory, where the shallow water table (seawater and water flowing under the surface from the continent) promotes capillary removal of a large amount of salts into the soil and to the surface as a result of intensive evaporation. Water-soluble salts and gypsum usually form a terrigenous-chemogenic crust (1-3 m) on solonchaks, in the mineral composition of which halite and thenardite are predominant.

Besides the contemporary marsh zone of the residual Aral Sea, solonchaks are widely developed in the Akpetki and in the center of dried-up former large bays: Adzhibai, Dzhil'tyrbas, Bozkol, and Sarycheganak.

Phytogenic sediment accumulation is occurring on sections of the contemporary dried-up bottom of the Aral Sea that are rapidly being overgrown. This is primarily true of the northwestern dried-up bottom of the Little Sea. There, thanks to year-round high moisture content of the dried-up clays (of hydromica-montmorillonite composition) formed as a result of erosion of Neogene—Paleogene bedrock, a thick herbaceous cover has formed. The products of dying-back of this cover are organogenic material for formation of contemporary phytogenic sediments in the form of a thin (several millimeters) phytogenic layer.

In other sections of the dried-up bottom, the plant cover is not as thick, and, accordingly, accumulation of phytogenic material is even less significant. On the whole, sedimentogenesis on the dried-up bottom on account of phytogenic material is slightly developed, since in aerial conditions (with the hot and dry climate of the Aral desert) organic matter is easily destroyed, without leaving any sediment.

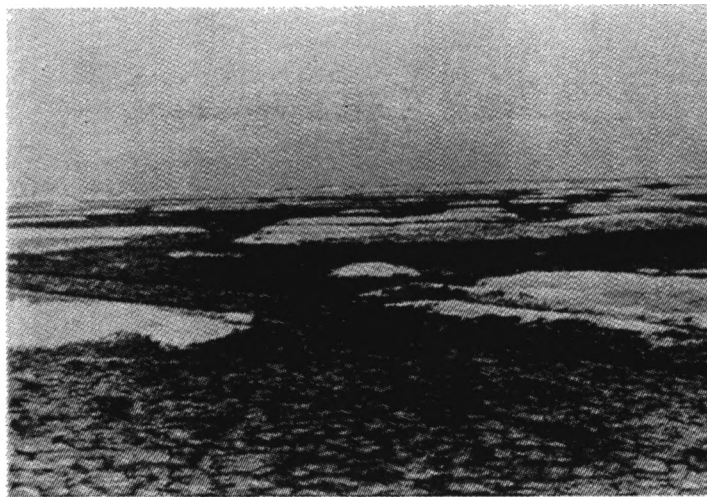


Fig. 3. Accumulations of salts on the surface of marine clays in Adzhibai Bay.



Fig. 4. Shrinkage cracks on clay soils of the dried-up bottom of the Aral Sea at Cape Torangly (west coast of the Little Sea).

DIAGENESIS ON THE DRIED-UP BOTTOM

We classify as diagenesis the transformations in sediments of the dried-up bottom that have occurred in them after they emerged from under the sea level. Diagenesis mostly leads to petrification of former bottom soils, but, along with this, the sediments that have formed can also be loosened with a change in their physical state (for example, with the transition of mirabilite to thenardite flakes).

The basic diagenetic transformations of sediments are reduced to salinization, desiccation, deflation, erosion, and overgrowth of them (see Fig. 2).

Salinization of soils of the dried-up bottom, which leads to their diagenesis after they emerge from under the sea level, is expressed in a change in their physicochemical state, petrification, etc., as a consequence of precipitation of salts at some depth and on their surface (Fig. 3), and evaporation of groundwater rising through capillaries (of which we spoke above). At first, carbonates are precipitated in the lower part of the profile, and gypsum higher up; and closer to the

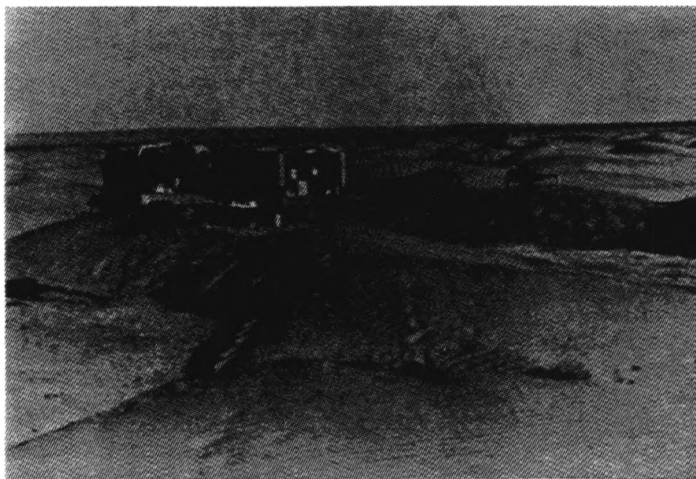


Fig. 5. Barchans formed as a result of deflation of sands in the wave-cut zone of the Aral Sea along the eastern shore of Kokaral Island.



Fig. 6. Erosion relief forms on the dried-up bottom west of Kaskakulan Island ("sheepbacks").

ground surface (and on the surface), water-soluble salts [8]. Diagenetic transformation of soils of the dried-up bottom as a result of salinization is noted essentially over its whole area, with varying degrees of intensity: from fractions of a percent of salts on desalinized sections up to 1.3-5% or more on solonchaks.

Desiccation of sediments of the dried-up bottom is a dynamic transformation caused by a reduction in the volume of marine soil due to evaporation of muddy waters. On the dried-up bottom of the Aral Sea, fine-grained (silt-clay) sediments are subject to the most intensive desiccation, cracking up into various-sized (up to 1-2 m across) blocks (Fig. 4). The depth of the cracks separating them reaches 1.5 m; the width, 10-15 cm. Vast areas of cracked marine silts are found, for example, at a certain distance (1-5 km) from the former shore of Adzhibai Bay (mainly in the eastern part of it), or on the northeastern dried-up bottom of the Little Sea. In desert conditions, shrinkage cracks are good absorbers of products of aeolian transportation of sediments. When they fill up with sandy aeolian material, the former monolithological clay and silt sediments acquire an essentially different material composition, thereby being subjected to significant (diagenetic) transformation in aerial conditions.

Deflation of dried-up coarse-grained bottom soils (sands that made up the flat bottom of vast shallows of the Aral Sea) has now led to formation of various-sized barchans (up to hundreds of meters in length and 4-5 m high) on considerable areas. These are mainly regions of the Eastern Aral dried-up bottom, and also small tracts of aeolian barchans in the western part of Adzhibai and Dzhylyrbas Bays, the northwestern part of Akpetki, in the northern and eastern parts of Kokaral Island (Fig. 5), and in the northeastern part of Sarycheganak Bay.

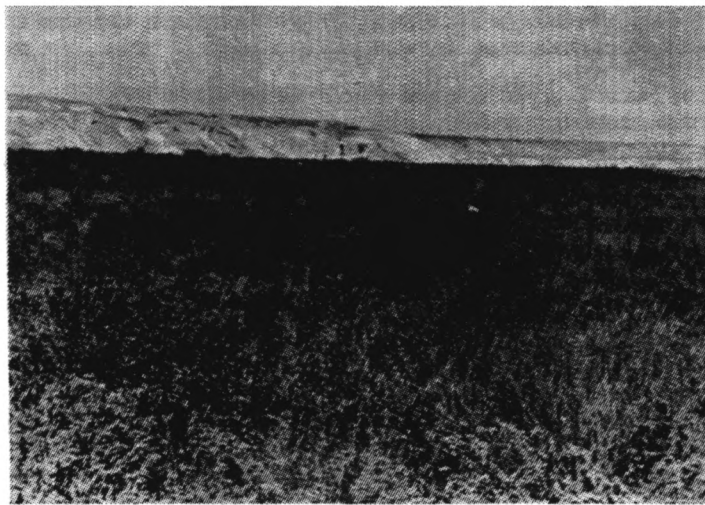


Fig. 7. *Atriplex* thickets on the western edge of Adzhibai Bay.

Other types of terrigenous sediments of the dried-up bottom (silts and clays) are almost not subject to deflation and do not have a large effect on transformation of the dried-up bottom. For evaluating the ecology of the Aral region it is important to determine the scale of deflation of loose chemogenic sediments (thenardite flakes).

Erosion relief forms are most clearly manifested along open seashores at the boundary of replacement of sandy sediments by silts and clays. Such erosion forms were first described by staff members of the Institute of Geography of the Academy of Sciences of the Kazakh SSR on the dried-up bottom west of Kaskakulan (Fig. 6), and they arbitrarily called them *sheepbacks*. Outwardly, these forms of sediment erosion are represented by gently sloping ridges arranged perpendicular to the shore (up to 1 m high and 0.5-1.5 m across, with a length of several meters) and the similarly eroded flat-bottomed gully depressions separating them. However, the genesis of these relief forms had not been unequivocally proven at that time. Only in the summer of 1990 were the conditions of their formation established. On August 17, 1989, we observed the mechanism that produces these relief forms near Cape Baigubekmurun at the Usturt scarp. There, at the boundary of the sea and land, sediments eroded into cellular ridges ("sheepbacks"), composed of dark-gray, sandy-clay, sandy-layered silts with plant remains (chalan), run off in the direction of the aquatory (from the waterline). The formation of these ridges occurs in the transition zone between the gentle and steep parts of the underwater sea slope, as a consequence of the action of sea waves running up on the shore. The width of the gully originating there is 1-5 m and even 10 m; their depth varies from 20 to 70 cm; and their extent, from several meters to several tens of meters. The surface of the "sheepbacks" clay elevations is flat, and on the bottom of the depression separating them lies brownish sand washed there from the direction of the shore. Under the sand (5-10 cm) lie clays of composition analogous to the elevated sections of the sea bottom.

We should say that, besides the "sheepbacks," the contemporary surface of former bottom sediments of the Aral Sea is complicated by linearly extended furrows "plowed" in their time by the bottoms of fishing ships trying to get as close as possible to the shore in shallow water. They are chaotically located, but sometimes perpendicular to the shore. The length of such furrows reaches several hundreds of meters, and their width and depth are 1-1.5 m. In places (for example, on the east coast of the Little Sea, north of the village of Bugun), individual flat-topped elevated sections located between such furrows on the former sea bottom are reminiscent of a roadbed, and when they narrow they are similar in form to the "sheepbacks" mentioned above (the genesis of which is natural, and not anthropogenic). Linear relief forms on the exposed bottom of the Little Sea at Cape Domalak (the northeastern part of Kokaral Island) are curious; true, they are most likely of tectonic origin. In satellite photographs, narrow (300-500 m) rectilinear bands (latitudinally oriented) stretching up to 2-4 km are clearly seen there.

We arbitrarily classified overgrowth of soils of the former sea bottom (see above) as diagenesis, since the "purity" of these sediments is disrupted by the change in their physical state as a consequence of the penetration of plants' root systems into the soil and an admixture of dead organic matter.

Researchers have established [6, 7, 10] that the species composition of plants covering the dried-up bottom changes as it ages. At first (in the second-fifth year after the sea recedes), the dried-up bottom is overgrown by halophytes in the following sequence: glasswort (*Salicornieta*), seablite (*Suaedeta*), and orache (*Atriplexeta*). Later (in the sixth-eighth years), as the soil is desalinized (further from the sea), halophytes are replaced by psammophilous vegetation. Tamarisk (*Tamarix*), azhrek (*Aeluropus*), reed (*Phragmites*), etc. appear. Subsequently, the plant cover of the dried-up bottom becomes close in its species composition to the cover of the adjacent desert. It has also been noted that the lithological composition of soils of the dried-up bottom significantly influences the zonality of the plants' distribution. Thus, for example, the primarily montmorillonite composition of clays of the northwestern dried-up bottom of Bol'shoi Sarycheganak Bay predetermined the exclusive occurrence of *Suaeda* there (from the former shore almost to the center of the bay). On sandy tracts of the dried-up bottom, psammophytes are found from the former shore almost to the marsh zone of the sea.

EFFECT OF SEDIMENTS ON THE ECOLOGY OF THE ARAL REGION

Anthropogenic desertification of the Aral region caused by lowering of the level of the Aral Sea (and due to a sharp reduction in inflow of river water into it) is an undoubted fact. Evaluation of the scale of the exposed sediments' effect on the surrounding environment is a different matter. Most researchers [4, 6, 7, 15] link the general desertification of the Aral region with: 1) the reduction in level of groundwater in the desert adjacent to the sea (which led to degradation of certain species of plants and animals), 2) aridization of the climate (the summer is hotter; the winter is colder; there are more dust storms, etc.), 3) drying-up of the abovewater deltas of the Amu Darya and Syr Darya (less evaporation due to transpiration), 4) removal of salts from the dried-up bottom of the Aral Sea (salinization of the adjacent desert), etc.

The question of the scale of influence of salts removed from soils of the dried-up bottom on the environment of the Aral region had not yet been resolved. It is impossible to prove by current research methods exactly which are salts are removed from the dried-up bottom of the Aral Sea, and which from other parts of the Aral region. As far as the high salinity of soils of the former abovewater deltas of the Syr Darya and especially of the Amu Darya, the facts indicate that the greater part of the salt accumulations there was formed as a result of capillary rise of groundwaters and evaporation of them, i.e., it is of local origin. Data from experimental observations of aeolian salt transfer in the Amu Darya delta [14] only indicate the fact of some influx of salts.

Attempts have been made to calculate the mass of salts transported by the wind on the dried-up bottom of the Aral Sea. The results of these investigations, which were based on different methods of calculation, showed [11, 19] that in 1984, on the average, about 43 million tons of salts was deflated on the dried-up bottom of the Aral Sea. There are no more or less reliable calculations of the amount of salts removed beyond the bounds of the dried-up bottom. By comparing the cited data with information on the centuries-old equilibrium in the balance between salts washed into the Aral Sea with the waters of the Amu Darya and Syr Darya (34.5 million tons) and the constant salinity of the seawater at the level of 9-10 g/liter (which was maintained as a result of precipitation of salts in seaside solonchaks and deflation of them from there), we can draw the conclusion that the past and present deflation of salts in the maritime zone of the Aral Sea are of the same scale [18, 19]. Hence follows the logical conclusion that deflation of salts from the contemporary dried-up bottom is hardly a direct threat to the ecology of the Aral region. The current ecological situation in the Aral region is of a catastrophic nature not because the sea is disappearing and having a negative influence on the surrounding environment, but due to the fact that extreme conditions for human life have been created in the Aral region, due to the absence of water suitable for economic and household use (the inflowing water is known to be highly mineralized), unsatisfactory industrial-production support of the population, and also poor housing and public-service conditions.

* * *

On the basis of what has been set forth, we can draw the following conclusions.

1. Sediments of the contemporary dried-up bottom of the Aral Sea were formed in two stages: in the stage of the sea's transgression (subaqueous sediments — sands, silts, clays, carbonates, gypsums, sapropel), and in the stage of regression caused by the anthropogenic factor (subaerial sediments — aeolian sands, salts).
2. In the aerial conditions of the contemporary dried-up bottom, sediments have undergone significant changes and diagenesis, leading to their lithification (desiccation, cracking), deflation, salinization, and overgrowth.

3. The catastrophic state of ecology in the Aral region is primarily due to the poor quality of drinking water entering the region, although, on the whole, the fact of desertification of the territory adjacent to the sea is not denied.

On the whole, the soils of the contemporary dried-up bottom of the Aral Sea are sediments of complex genesis formed under the influence of the anthropogenic factor, which has caused regression of the sea. Since the subaqueous conditions of the sediments' accumulation (the transgressive stage) have been replaced by subaerial conditions (the regressive stage) in an extremely short period (many times less than natural), information about peculiarities of the lithological condition of dried-up soils and their diagenetic transformations is of definite interest for reconstructing paleosituations of the past. It seems that not all researchers visualize clearly enough what complex physicochemical (diagenetic) transformations of sediments (and also disruption of the region's ecology) are occurring with the change in sedimentation situations characterized in the present work. The author hopes that the factual data presented will help, to some degree, to develop ideas about these processes.

LITERATURE CITED

1. L. S. Berg, "The Aral Sea," *Izv. Turkestansk. Russk. Geograf. O-va*, No. 5, St. Petersburg (1908).
2. N. G. Brodskaya, "Bottom deposits and sedimentation processes in the Aral Sea," *Tr. GIN AN SSSR, Ser. Geol.*, No. 115, (1952).
3. M. G. Valyashko, "Natural classification of salt lakes according to the chemical composition of their brines," *Dokl. Akad. Nauk*, 22, No. 7, 824-825 (1939).
4. I. P. Gerasimov, N. T. Kuznetsov, A. S. Kes, and M. E. Gorodetskaya, "The problem of the Aral Sea and anthropogenic desertification of the Aral region," *Probl. Osvoeniya Pustyn'*, No. 6, 3-10 (1984).
5. V. P. Zenkovich, "Bottom deposits of the Aral Sea," *Byul. MOIP, Otd. Geol.*, 22, No. 4, 34-51 (1947).
6. S. K. Kabulov, *Changes in Desert Phytocenoses as a Result of Aridization (on the Example of the Aral Region)* [in Russian], Fan, Tashkent (1990).
7. R. K. Kievskaya, "Formation of the landscape of the drying-up strip of the eastern shore of the Aral Sea in the region of the deltafront of the Syr Darya," *Probl. Osvoeniya Pustyn'*, No. 5, 18-24 (1975).
8. V. A. Kovda, *Origin and Conditions of Salinized Soils* [in Russian], Vol. 1, *Izd-vo AN SSSR, Moscow-Leningrad* (1947).
9. E. G. Maev, S. A. Maeva, and S. D. Nikolaev, "Cross section of bottom deposits in the central part of the Aral Sea," in: *Paleogeography of the Caspian and Aral Seas in the Cenozoic* [in Russian], Part II, *Izd-vo MGU, Moscow* (1983), pp. 122-132.
10. G. B. Makulbekov, "Vegetation of the Bosai site and changes in it," *Probl. Osvoeniya Pustyn'*, No. 5, 31-36 (1979).
11. N. F. Mozhaitseva and T. F. Nekrasova, "Method of calculating wind removal of salts from the dried-up bottom of the Aral Sea," *Probl. Osvoeniya Pustyn'*, No. 6, 15-21 (1984).
12. A. I. Perel'man, *Geochemistry of Epigenetic Processes* [in Russian], Nedra, Moscow (1965).
13. V. I. Popov, S. A. Makarova, and A. A. Filippov, *Guide to Determining Sedimentary Facial Complexes and Procedure for Facial-Paleogeographic Mapping* [in Russian], Gostoptekhizdat, Leningrad (1963).
14. R. M. Razakov and K. A. Kosnazarov, "Aeolian removal and deposition of salt and dust particles in the Aral region," in: *Problems of the Aral Sea and Environmental-Protection Measures* [in Russian], SANIIRI, Tashkent (1987), pp. 24-32.
15. A. A. Rafikov, *Natural Conditions of the Drying-Up South Coast of the Aral Sea* [in Russian], Fan, Tashkent (1982).
16. I. V. Rubanov, "New data on the structure of bottom sediments of the Aral Sea," *Probl. Osvoeniya Pustyn'*, No. 2, 40-44 (1982).
17. I. V. Rubanov, "Sulfate-bearing sediments of the Aral Sea, their structure and composition," *Litol. Polezn. Iskop.*, No. 1, 117-125 (1984).
18. I. V. Rubanov, "Composition and status of contemporary sediments of the southern dried-up bottom of the Aral Sea," in: *Problems of the Aral Sea and Environmental-Protection Measures* [in Russian], SNIIRI, Tashkent (1987), pp. 56-63.

19. I. V. Rubanov and N. M. Bogdanova, "Quantitative evaluation of salt deflation on the drying-up bottom of the Aral Sea," *Probl. Osvoeniya Pustyn'*, No. 3, 9-16 (1987).
20. I. V. Rubanov, D. P. Ishniyazov, M. A. Baskakova, and P. A. Chistyakov, *Geology of the Aral Sea* [in Russian], Fan, Tashkent (1987).
21. L. B. Rukhin, *Principles of Lithology* [in Russian], Gostoptekhizdat, Moscow (1961).
22. O. E. Semenov, L. P. Tulina, and G. N. Chichasov, "Ecological conditions in the Aral region and monitoring of the surface climate," in: *Natural and Socioeconomic Problems of Ecologically Destabilized Regions* [in Russian], Izd-vo AN SSSR, Moscow (1991), pp. 109-110.
23. N. M. Strakhov, N. G. Brodskaya, and L. M. Knyazeva, *Formation of Sediments in Contemporary Bodies of Water* [in Russian], Izd-vo AN SSSR, Moscow (1954).
24. N. M. Strakhov, *Principles of the Theory of Lithogenesis* [in Russian], Vol. 1, Izd-vo AN SSSR, Moscow (1960).
25. P. P. Timofeev, Yu. G. Tsekhovskii, and A. P. Feofilova, "Soil lithogenesis and its role in formation of sedimentary rocks," *Litol. Polezn. Iskop.*, No. 4, 18-38 (1977).
26. V. N. Kholodov, "The role of sandy diapirism in interpreting the genesis of mud volcanos," *Litol. Polezn. Iskop.*, No. 4, 50-66 (1978).
27. Yu. P. Khrustalev, S. A. Reznikov, and D. S. Turovskii, *Lithology and Geochemistry of Bottom Sediments of the Aral Sea* [in Russian], Izd-vo Rost. Un-ta, Rostov-na-Donu (1977).
28. E. V. Shantser, "Synopsis of teaching about genetic types of continental sedimentary formations," *Tr. GIN AN SSSR*, No. 161, 25-37 (1966).
29. M. S. Shvetsov, *Petrography of Sedimentary Rocks* [in Russian], Gosgeolizdat, Moscow (1958).

THE EVOLUTION OF SEDIMENTARY BASINS IN CONTINENT-ISLAND ARC COLLISION ZONES

A. I. Konyukhov

UDC 551.461.8:551.2

In the article, we discuss various stages in the evolution of sedimentary basins (rift, backarc, forearc, etc.) located in the collision zone between the margin of the African continent and the Aegean and Calabrian volcanic arcs. We show that redistribution of materials and fluids took place between different complexes of the sedimentary cover during certain stages in the evolution of the area; this was accompanied by diapirisms, mud volcanism, and formation of a system of anticlinal folds.

Zones where collisions between two continent megablocks take place are distinguished by especially complex structure. As a rule, one continent is involved through a passive continent margin and the other through a complexly structured transitional region, including volcanic island arcs, relics of defunct oceanic structures mountain-fold structures arising in their place, and buried parts of old or young platforms. Together, these structures form a heterogeneous tectonic mosaic includes at various types of sedimentary basins. Five types of such basins can be distinguished: backarc, forearc, rift, ancient continental-margin, and relic heterogeneous developing from foredeeps. The latter include basins formed early on and situated at the rear of the current collision zone. They have formed where Alpine and Kimmerian mountain-fold systems abut old and (or) relatively young platforms and include fragments of defunct oceanic structures. The Black Sea, Ligurian, and Southern Caspian basins are examples of this type.

Another type of basin includes troughs formed relatively recently in areas directly to the rear of volcanic island arcs where splitting and subsidence of continent crust predominate. Examples of such backarc formations include the basins of the Tyrrhenian and Aegean seas. The small Southern-Aegean trough situated between the Aegean volcanic arc itself and the island of Crete is an example of a forearc basin.

Basins of ancient passive margins located directly within collision zones of continent megablocks are very broad and complexly structured. Such basins include the Mediterranean-Sea region as well as structures located on the ancient, essentially Gondwana margin of Africa. They also include relics of defunct oceanic formations left over from the Tethys Sea and ancient volcanic arcs which have lost their volcanic activity, Cyprus, for example, as well as macrobasins divided into several basins or sub-basins, such as the southern part of the Algiers-Provence basin and a large part of the Ionian Sea.

A fifth variety includes basins of purely rift-related origin, composed of fragments of ancient continental-margin blocks and island-arc systems, on the one hand, and areas of relatively young oceanic type crust, on the other. The clearest example of such a basin is the central and northeastern part of the Algiers-Provence basin.

BACKARC AND FOREARC TROUGHS

Backarc troughs with ancient continental substrate to some degree disrupted by faulting are the most simply formed basins. Typically, these are strongly eroded crustal blocks of Hercynian or Kimmerian consolidation covered by a weakly developed sedimentary mantle. Epi-platform or mountain-fold structures line the peripheries of such troughs. In the recent past, these basins were parts of intermontaine continental landmasses subjected to substantial denudation. The bottom surface of such a backarc trough now shows an overall incline toward the volcanic arc bounding it. Systems of old rivers and rivelets have cut into it and such a trough is partially filled with sediments. These are relics of drainage systems existent during low stands of the sea. The sedimentary cover in backarc troughs, predominately composed of Pliocene-Quaternary sediments, is generally thin. However, lenses of older sedimentary rock preserved in individual areas in more deeply subsided crustal blocks (for example, carbonate platforms were widely occurring during the Mesozoic) are of interest for oil and gas exploration. Such troughs are typified by small-block, keyboard-like structure in which some of

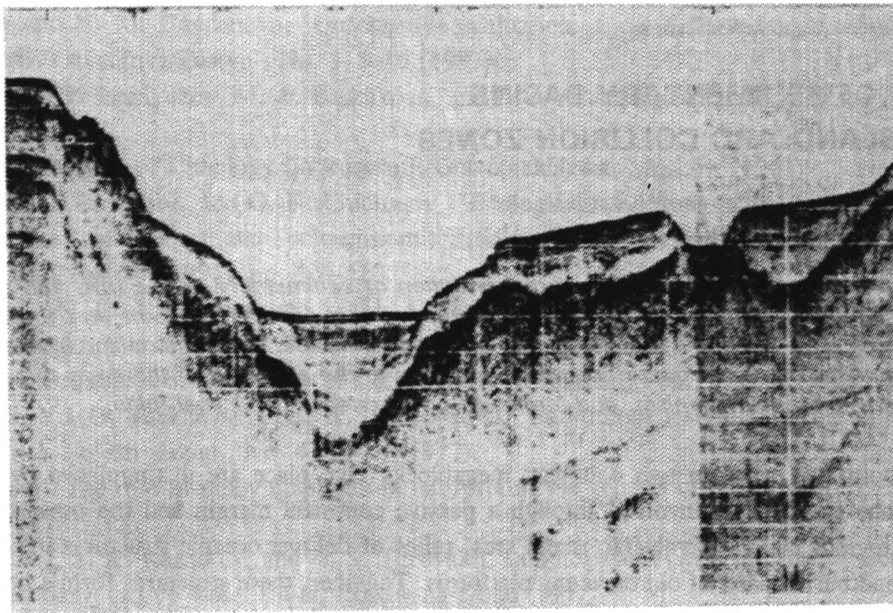


Fig. 1. Erosion channels on the bottom of the Tyrrhenian Sea, northern part.

blocks are markedly uplifted and the other blocks situated between uplifted ones have subsided. It is precisely within these subsided blocks that one finds sedimentary strata of substantial thickness, relics of an ancient sedimentary cover. More active accumulation of recent sediments takes place in such areas.

In the case of the Aegean Sea, controversy continues over clastic deposits of shallow-water-marine origin, including both sandy-silty and clayey varieties. During the Recent epoch, there was accumulation of material mobilized by seawater during abrasion of steep coastal escarpments bordering numerous islands with mountainous relief. Skeletal fragments of benthic organisms, including shells of foraminiferans and molluscs, as well as sponge spicules, are mixed together with terrigenous material. In stony areas of the seafloor, siliceous sponges were the main producers of organic matter. The size distribution of the sediments was determined by the wave regime. Therefore, sands and sandy silty muds predominate at depths to 30 m and silty clay and clayey sediments predominate below this depth. Around islands of volcanic origin, above all, around Santorin Island, extensive areas of the seafloor are covered with volcanic ash to thicknesses often exceeding 2-3 m. The ash is the result of a huge catastrophe which took place 3.5 thousand years ago: the eruption and bursting of a volcanic edifice, the remains of which persist as small fragments jutting above the surface of the sea in the form of small islets.

During a time of sharp drop in sea level in the Pleistocene, substantial areas of the Aegean seafloor surfaced and were transformed into small river valleys. The rivers of these valleys downcut marshy plains primarily extending southward toward the southern Aegean basin, which became the terminal basin (the present depth of the seafloor in 600 m). The bulk of volcanogenic and terrigenous material eroded from the land fed into this area. Terrigenous clastics in the form of submarine turbidity currents were carried into the basin from the island of Crete and islands of the Kikladhes group. Evidence for this includes packets of recently described turbidites found at the bottom of the southern Aegean basin [15]. Turbidites of sandy quartz-petroclastic composition, material carried in from islands of the so-called outer arc (the islands of Crete, Rhodes, etc.), are especially abundant.

The basin of the Tyrrhenian Sea can be considered a backarc basin formed during the Late Cenozoic after creation of the Calabrian (Liparian) volcanic island arc. During the earliest stages in the evolution of the basin, a process similar to that now proceeding in the Aegean Sea was probably taking place. Actually, the crust, at least in the northern and central parts of the Tyrrhenian basin, is continental, although buried at substantial depths. As in the Aegean Sea, it has evolved into blocks and is covered by a rather thin sedimentary mantle. On seismic profiles, one can also detect submarine channels probably left over from the last glaciation. Cutting through the layers of unconsolidated sediments, they often reach the consolidated part of the sedimentary cover (Fig. 1), the surface of which is generally inclined toward the arc

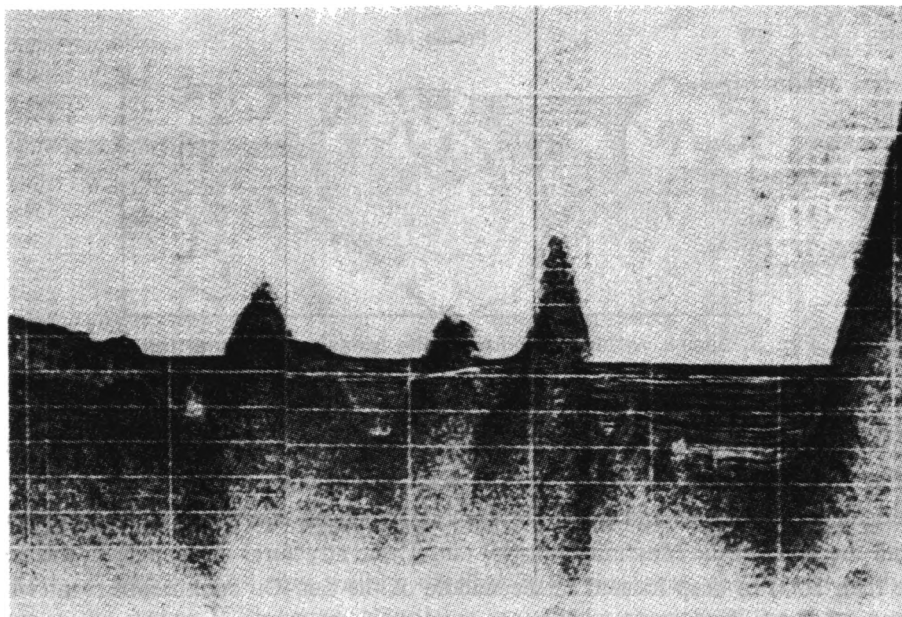


Fig. 2. Structure of the sedimentary sequence in the southern part of the Tyrrhenian Sea (in the region between the Vavilov and Marcel seamounts).

and buried to depths ranging from 400 (in the north) to 3000 m (in the south). Deep-water environments predominate here and mainly clayey, finely washed muds containing interlayers of volcanic ash and manganiferous sediments are being deposited.

The near-Appennine part of the Tyrrhenian Sea is composed of fragments of Mesozoic carbonate platform buried to depths of more than 1000 m. In the overlying Quaternary sediments, manganese-siderite nodules, radiolarian oozes, radiolarian chert, gypsum-bearing sediments, as well as clayey muds, have been described [9].

The layered structure of the sedimentary sequence in the central of the Tyrrhenian Sea (Fig. 2) shows, above all, the presence of turbidites formed during an epoch of glacio-eustatic drops in sea level. In this part of the sea, we find the large volcanic Vavilov and Marcel seamounts, composed of basaltic lavas. These structures resulted from the initial spreading processes. Thus, the Tyrrhenian Sea is in the next stage in the development of a backarc basin following that found in the Aegean basin.

The Adriatic basin is the most interesting backarc basin in the Mediterranean Sea from the point of view of oil and gas content. In contrast to the others, it has a fairly thick sedimentary cover, the lower half of which is composed of carbonate platforms of the Late Mesozoic–Early Cenozoic [14]. These relics of ancient shallow water carbonate shelves and reefs are covered by terrigenous flysch and flyschoid formations of the Late Eocene–Oligocene [13].

The above-described Southern Aegean basin, situated between islands of the Aegean volcanic and outer arcs, is first and foremost among the forearc basins in the vicinity of the Mediterranean Sea. It is recently formed and does not have a well developed sedimentary cover. In the central sector of the Mediterranean Sea, the part of the Ionian seafloor which lies between the eastern slope of the island of Sicily and the base of the Appennine "boot," in other words, the continental slope of Calabria, seems to be a forearc basin. Within this small, southward-extending space, formation of the Messinian submarine alluvial fan, a multilobed embankment structure breaking up into a number of smaller fans, is taking place [5]. The latter are geographically associated with canyons downcutting the submarine slopes of Sicily, including the base of the Etna volcano. The largest and deepest submarine canyon is located on a continuation of the Strait of Messina separating Sicily from the Calabrian projection of the Appennine Peninsula. Series of weakly consolidated turbidite sediments (typical terrigenous and volcanic–terrigenous flysch) lie here on Late Miocene salts and marly Pliocene formations ubiquitous in the Ionian basin.

Despite the fact that the average thickness of the terrigenous sequence apparently does not exceed 1-1.5 km, the uneven distribution of sediments in different parts of the abyssal fan causes repeated reactions in underlying Messinian

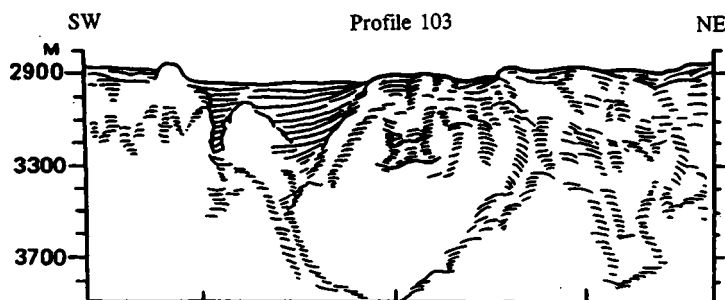


Fig. 3. Basins within the body of the Messinian alluvial fan.

salts, which appear to have very uneven surfaces on seismoacoustic profiles. A typical cross-section abounds with projections and depressions (Fig. 3) and, toward the south, takes on a cobblestonelike appearance. It is assumed that the surface of the salt consists of closely nestled, large and small salt domes. Structures equivalent to the Hellenic abyssal trench are apparently buried beneath the body of the Messinian alluvial fan. These structures appear in the bottom topography as small depressions more than 3000 m deep located in the middle of the fan. On such depression, which we surveyed in detail during a cruise of the R/V *Moskovskiy Universitet* during 1988-1989, is surrounded by large walls 700-800 m high. In the axial part of this depression, which has been named the MGU depression, rare formations known as homogenites are accumulating [5]. Data on the deep structure of the crust in this region is lacking; therefore, it is at present difficult to assess prospects for oil and gas in this region.

HETEROGENEOUS RELIC BASINS AND TROUGHS OF RIFT ORIGIN

Rift basins located at collisions between alpine mountain-fold structures and platform structures are substantially more complex, both with respect to structure and geological history. The Algiers-Provence and Ligurian basins are objects of special controversy. Although relatively little is known concerning the deep structure of these latter basins, since a thick screen of Messinian salts hampers from their investigation by geophysical methods, it is assumed that opening of the Algiers-Provence basin and the western axial part of the Ligurian basin took place during the Oligocene. During the Recent epoch, the Ligurian basin has been an example of a structure identifiable as a forearc basin at an abutment between platform blocks (in this case, the Coriscan) and mountain fold structures of the Savoy Alps and the Apennines. Only a narrow axial zone in the western part of the Ligurian Sea is composed of suboceanic or oceanic crust [12]. In other areas, continental crust is present. The stage of sedimentary cover, which is no more than 2-4 km thick, is composed of pre-Messinian terrigenous complexes corresponding to the stage of riftogenesis and basin formation. The Messinian salts have been identified as an intermediate stage. The upper stage is composed of Pliocene carbonate and Quaternary terrigenous sediments. A series of turbidites forming small submarine alluvial fans (the alluvial fan of Vara River is the largest) are included among the latter.

Relic basins, especially the Black Sea and the Southern Caspian, are characterized by heterogeneous structure and complex geological history. The sedimentary cover in such a basin can be broken down into several stages, with two or three stages distinguished by distinctly heterogeneous structure. The lowest of these marks the position of old troughs and sags which took form during the initial stage in the creation of the relic basin or its individual parts. Stages with heterogeneous structure are separated by intervals characterized by relatively uniform and undisturbed bedding. As a rule, these deposits are consistent in thickness and facial origin, and were formed in monotypic depositional environments under conditions of uniform dispersion of sedimentary material. Such intervals, although representing whole epochs or even periods, are typically not very thick, since they correspond to stages of relative tectonic inactivity. During formation of these intervening intervals in the section, abyssal redistribution of material and fluids was usually slight, primarily because of uniformity and weak intensity of sedimentation. As a result, deep-lying sedimentary complexes have had almost no interaction with overlying beds and the surface.

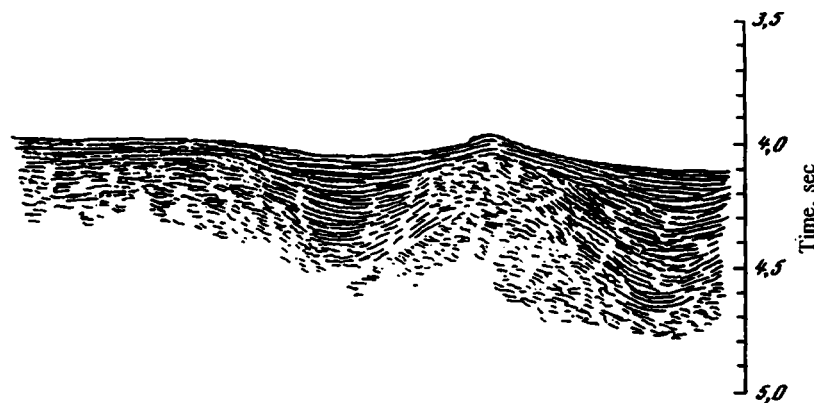


Fig. 4. Anticlinal fold in sedimentary cover at the periphery of the submarine alluvial fan of the Nile River.

During activation of tectonic processes mainly affecting basin-rim areas, the pattern of dispersal of sedimentary material existing prior to the system is disrupted. New large-scale depocenters build up; these are zones in which large amounts of sediment previously uniformly distributed over a large area have accumulated. The amounts of terrigenous clastic material and clayey suspension brought by rivers from the basin borders also sharply increase. So depocenters are most frequently located in the pre-mouth areas of rivers, where deltas and submarine alluvial fans form. After several thousand years, even 1-2 million years, thick sedimentary bodies which merge together form at the basin periphery; when buried, these bodies appear as old sags. Their outlines in the final state are not controlled by faults in the basement, along which faster or slower burial of individual blocks takes place. Actually the rate of burial of the crust, previously fairly uniform, becomes distinctly uneven: it becomes faster in depocenter zones associated with reactivated faults and slower in areas adjacent to them. A new, upper belt of heterogeneity arises in the composition of the sedimentary cover.

Accumulation of weakly consolidated masses of sediment is accompanied by burial of previously formed beds to greater depths, where catagenetic processes are sharply activated. However, in the neighborhood where downwarping is still not substantial, catagenesis in the sediments is, as usual, retarded; this results in disruption of homogeneous fields of pressure and temperature at depth. As a result, the most plastic rocks, the salts, begin to flow, while initially moisture-saturated rocks, primarily clays, are compacted and lose surplus sedimentation moisture and, consequently, interlayer moisture, which results in beds with reservoir properties. Discharge, previously directed toward the basin rim, now becomes possible from depocenters to adjacent deep-water areas along seam pitches. Although this movement soon becomes complicated by the emergence of an entire network of listric and other faults, the strength of fluid flow in this direction increases over time.

However, real possibilities for draining of surplus fluids from the periphery to the center of a sedimentation basin are sharply limited because, while the majority of reservoir beds dip in this direction, other beds are consistently sealed off from the surface by overlying sediments. If the volume of fluids is not very large, the process is restricted by bulges in a number of reservoir beds, accompanied by the formation of large isoclinal folds in the upper part of the sedimentary cover. Such folds can be found along the periphery of thick, homogeneous sedimentary bodies in other marine basins, for example, before the front of the submarine alluvial fan of the Nile River (Fig. 4).

Often, fluids begin to accumulate in near-fault parts of fault-disturbed reservoir beds, where local stress foci are generated. The participation of catagenetic hydrocarbon generation and transformation of swelling varieties of clay into nonswelling varieties sharply increases the volume of fluids released into the reservoir environment, as a consequence of which, zones of anomalously high formation pressures are generated at depth near depocenters. The time arrives when the quantity of fluids trapped in a sealed-off reservoir increases so much that disruption of the structure of the enclosing rock and corrosion of the grains of the enclosing rock take place. At fault intersection, i.e., in the very weak zones where fluids accumulate, very large cavities filled with a tightly a compressed sedimentary-fluid mass (slurry) are created. These cavities are probably somewhat reminiscent of magma chambers in which molten magma is raging. The slurry begins to make its way up to the surface. As a result, diapir structures are generated, and if the fluid flow is especially great, mud

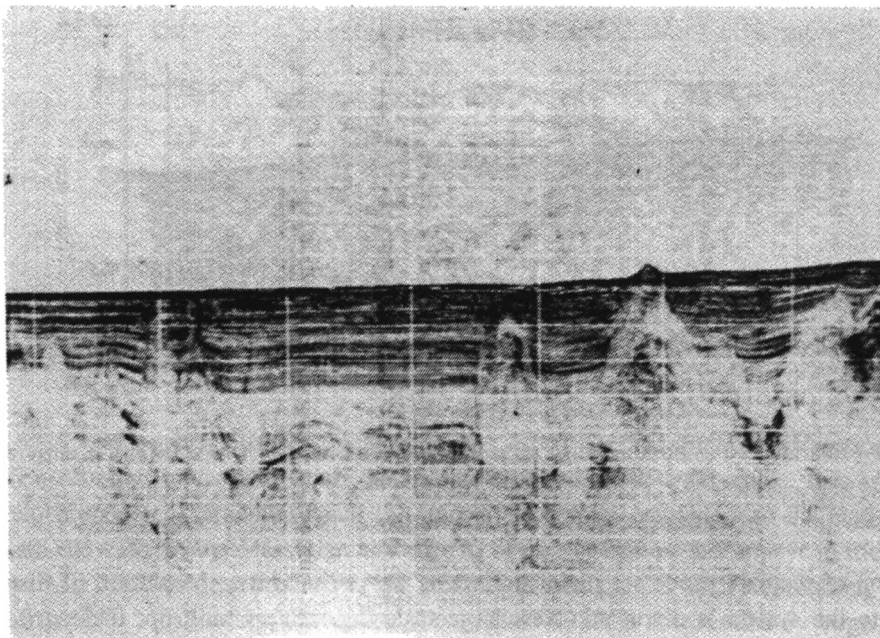


Fig. 5. Diapiric structures and mud volcanoes (?) in the deep-water part of the Ligurian Sea.

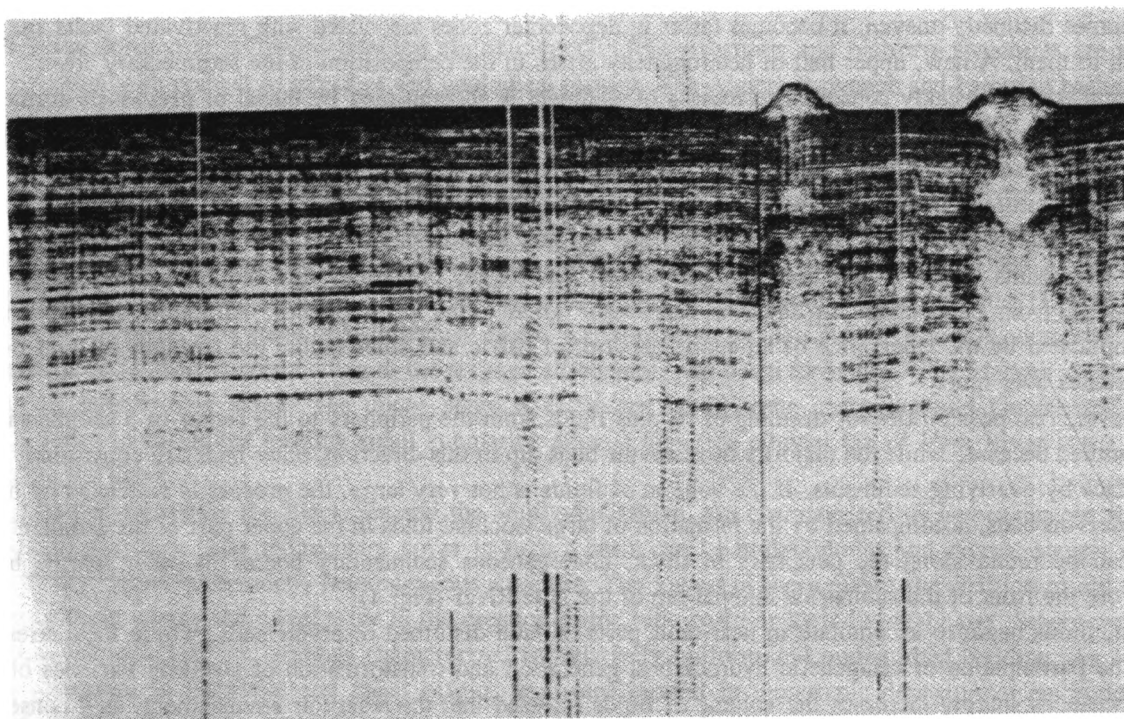


Fig. 6. Submarine mud volcanoes in the Western Black Sea basin.

volcanoes emerge over time. Such formations have been discovered in the Gulf of Genoa within a belt of submarine alluvial fans (at the distal parts of the fans (Fig. 5)), in the western Black Sea basin along a pinch out of the Dnieper-Dnester and Dunay abyssal fans (Fig. 6), and in the southern Caspian basin before the old delta front of the

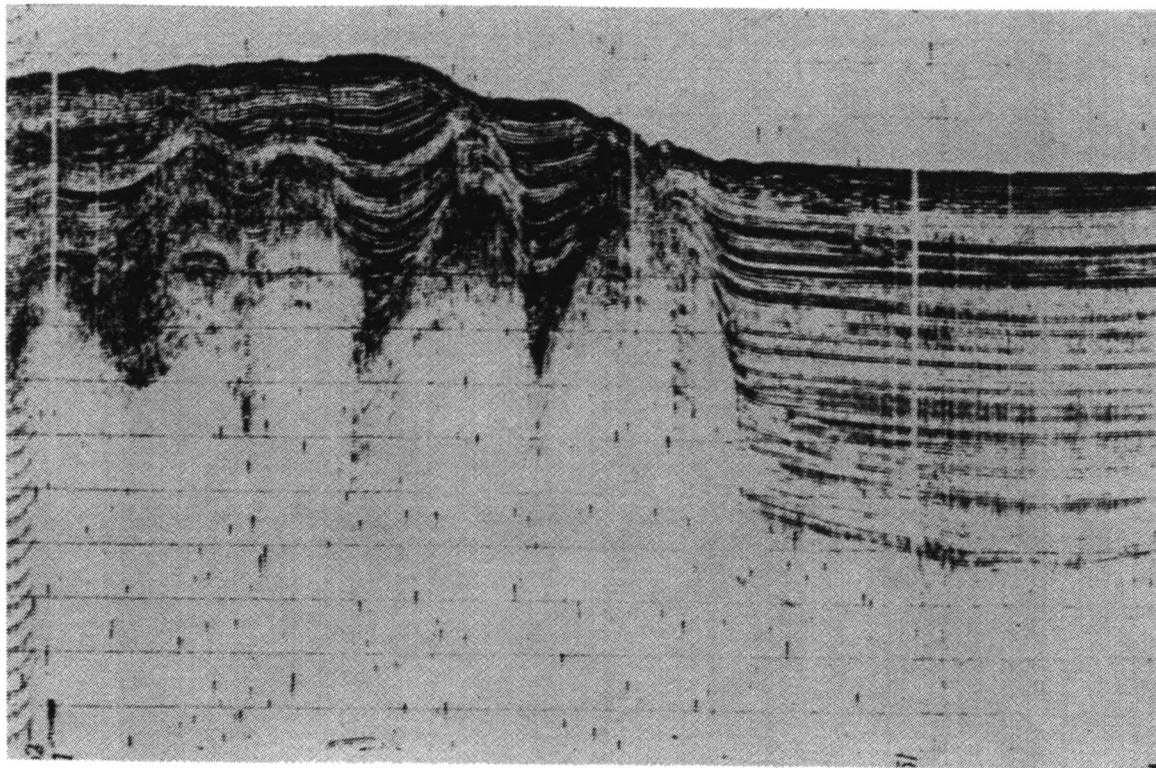


Fig. 7. Anticlinal folds complicating the continental slope of Southern Crimea.

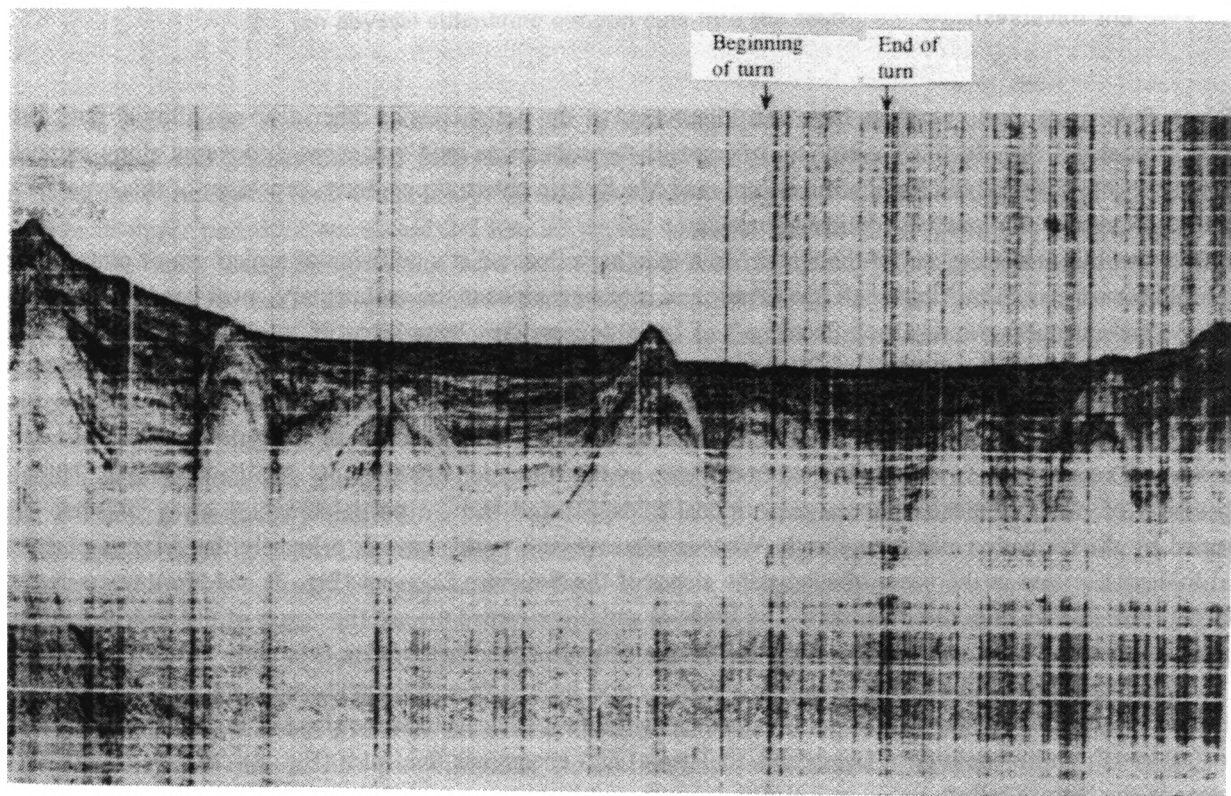


Fig. 8. System of anticlinal folds at the base of the continental slope of the Northwestern Caucasus in the Black Sea.

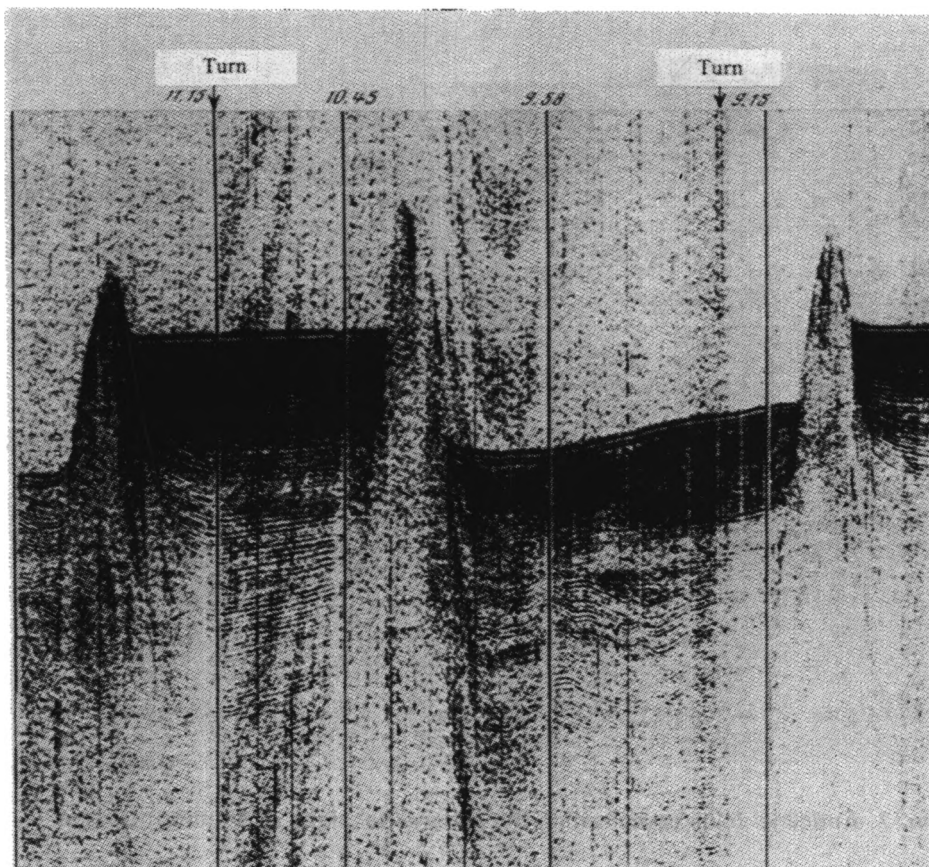


Fig. 9. An anticyclinal fold expressed in the seafloor topography and serving as a barrier to the passage of turbidity currents in the southwestern part of the Black Sea (along different traverses).

Volga River. Submarine mud volcanoes have been discovered at the peripheries of other deep-sea alluvial fans formed in oceans at a continental rise. In this connection, one recalls the submarine mud volcanoes discovered along extensions of submarine-delta complexes of the Indus, Mississippi, and MacKenzie rivers. Apparently, processes of this type are typical of many basins found within passive continental margins.

However, this is not the end of the matter. In a relic basin located at a collision of a platform or plate with young mountain-fold structures of the Alpine belt, the creation of heterogeneities in the sedimentary cover has had large-scale and far-reaching consequences. At the back "corners" of large depressions, complexes of weakly consolidated (primarily clayey) deposits formed in depocenters of Oligocene–Miocene age in shallow-marine and deltaic environments are now undergoing strong compression. This is a result of sharp subsidences of the bottom during the Pliocene–Pleistocene, with the above-mentioned back "corners" relocated at the base of a large submarine slope as a result. Redistribution of fluids between clay and reservoir beds was not limited in this case by the formation of sealed-off diapiric structures. This resulted in compression of plastic deposits into large anticyclinal folds [3] and then to partial breaking away of such deposits, accompanied by the formation of thrust sheets. What is controversial in this case is primarily the systems of submarine anticyclinal folds discovered at the bases of submarine slopes of the Southern Crimean (Fig. 7) and Northwestern Caucasus [3, 6] during seismic studies in the Black Sea. The limbs of anticlines turned toward the center of the basin are substantially steeper than those of opposite attitude. Data from deep seismic sounding indicate that these structures are generally faulted at depth. Disruptions in continuity of beds, accompanied by loss of correlation, can be traced to depths of several kilometers [7]. Systems of similar swivels-folds extend along the foot of the submarine slope of the Northwestern Caucasus for up to 100 km (from the vicinity of Gelendzhik to Tuapse) and encompass five folds (Fig. 8). The crests of only two of them appear in the bottom relief.



Fig. 10. Limb of an anticlinal fold forming at the base of the continental slope of the Apennines in the Ligurian Sea (an abyssal submarine canyon cuts into the fold).

One of these crests rises 300-400 m above the surrounding floor and even acts as a dam, a barrier against turbidity currents of terrigenous material gathered from the shelf and slope. As a consequence, the level of sediment deposits along the northeastern limb of the fold is 50 m higher than on the other (southwestern) side (Fig. 9). The width of the fold in its upper part does not exceed 2-3 km. At depth, widths substantially broaden due to flattening of the limb rotated toward the shelf. Thus, the growth of individual anticlines controls the rate of sediment deposition in this region. This is true despite the fact that rates of accumulation of terrigenous material are very high here, since the folds are located in a zone of influence of drift from the paleo-Kuban, from which a submarine alluvial fan formed during the Pleistocene.

If we assume that growth of anticlinal folds will continue for a long time, with the "pockets" between the folds being filled with sediments as before, then the time will arrive when they will be lifted to the level of the shelf and then brought up on dry land. In this case, we would be considering a new anticlinal zone, a foreland similar in many respects to that which extends along the coast of the Caucasus in the vicinity of the towns Novorossiysk and Gelendzhik. It is important to note that the rocks which will be eventually exposed in the cores and limbs of these rises will be identical in pattern of origin to those now forming the coastal excarpments and the ridges rising above them. There is controversy concerning turbidite series (actually terrigenous rather than carbonate in composition) i.e., concerning deposits known as flysch. At the crest of one of the anticlinal folds appearing in the bottom relief, we were actually able to bring up core composed of packets of thin-layered turbidites, including layers of terrigenous and pyrite-rich sand interbedded with dark-blue and blue clay. The turbidites are Late Quaternary in age and frequently include numerous fragments ("crumbs") of argillite and compacted clay scoured from the submarine slope [3].

Thus, we cannot rule out the possibility that we are directly witnessing the formation of a new mountain-fold system, which, with time, will rim the Black Sea margin of the Caucasus. If this is so, we are witnessing a mountain-form-

ing process in which a soft sedimentary cover is being gradually transformed, consolidated, and relieved of sedimentation water and water of other types to form a mountain-fold region in a rigid metamorphosed framework.

If the process of these transformations were to remain at this stage as a result of changing tectonic conditions, the northeastern Caucasus part of the Black Sea would undergo uplift and conversion to dry land, and a structure of the foredeep type with folds reminiscent of folds of the Tersk-Sunnzhensk zone would be formed at the site of the Tuapinsk basin, now identifiable at the base of the submarine slope. In the cores of submarine anticlinal structures, there are Maikopian sediments, most probably of shallow-marine and deltaic origin, as indicated by investigations of clay breccia from the peaks of submarine mud volcanoes. The latter were discovered in 1989-1990 in the western basin of the Black Sea [4]. The discovery of gas-hydrates in the composition of mud breccia suggests movement of hydrocarbon-fluid currents from depths to the seafloor surface.

It is interesting that fold formation in the sedimentary cover takes place in the eastern part of the Ligurian basin. Here, one fold is located in the lower part of the continental slope of the Apennine Peninsula. A deep canyon, along which turbidity currents move, has been cut into its northern limb. The canyon is not filled with sediments, i.e., is active (Fig. 10).

At a distance of 6-8 miles seaward of this profile, a different type of disruption in the sedimentary cover has been discovered. It manifests primarily in the form of large and small diapiric structures. Several of these reach the seafloor surface and are probably already transformed into mud volcanoes (see Fig. 5). All of them are links in a chain of processes associated with redistribution of fluids and solids at depth in certain sedimentary basins. Formation of deposits of oil and gaseous hydrocarbons are the most important result.

SEDIMENTARY BASINS OF AN OLD PASSIVE CONTINENTAL MARGIN

Unusual phenomena take place in the depths of a basin of an old, passive margin located in the collision zone with a volcanic island arc. There is controversy concerning the African margin of the Ionian Sea, a fragment of the margin of Gondwanaland which served as the southern margin of the Tethys Ocean during the Mesozoic and Cenozoic. During later epochs, a gigantic submarine rise, the Eastern Mediterranean Ridge, formed directly in front of a collision zone in the Ionian Sea; the crest portion of this rise has a cobblestonelike appearance on seismoacoustic profiles. It is assumed that this is a surface of Messinian salts covered by a thin mantle of Pliocene-Quaternary sediments. The salts form a very thick (2-3 km) screen preventing propagation of seismic waves; this complicates the investigation of deep structure in this part of the Ionian Sea.

However, in areas where Messinian evaporites are very thin or entirely lacking, there are structures in the upper part of the sedimentary cover which were initially mistaken for salt stocks, but which proved to be clay diapirs and mud volcanoes. In one of these zones, coinciding with the northern slope of the Mediterranean Ridge south of the Pliny abyssal trench, we were able to survey several domal structures with tops only partially covered by recent sediments. Recent sediments were completely lacking on one such structure. What is interesting here includes not only the usual mud volcanism accompanying the rise to the surface of large masses of poorly consolidated clay deposits containing fragments of diverse rocks (sandstone, siltstone, dolomite, and limestone), but also processes of more complex nature, in which sands of very diverse grain size but primarily petroclastic-quartz composition with an admixture of grit-sized grains and silty and clayey material rise up from the depths along with plastic clay.

Nevertheless, separately standing domes of apparently mud-volcanic origin are not very abundant formations. There is a predominance of small, short forms complicating the surface of a broad upwarped area. One of the domes we surveyed has a diameter at the base of ~2.5 km; the diameter at the top does not exceed 1 km. The structure rises 80-90 m above the surrounding seafloor. The top of the dome is a flat area inclined toward the south, where it grades into a fairly steeply dipping slope. From the north, the dome is bounded by a steeper slope; this is especially pronounced in the upper portion. Core containing terrigenous sand was collected from precisely this dome.

The discovery of signs of bedding of a more lenticular than irregular character was surprising. The sediments are much more consolidated than the recent muds occurring at depth. They are dark-brown and give off a strong odor of hydrogen sulfide. At a depth of 0.5 m from the seafloor surface, they contain brine in a concentration exceeding the salt concentration in typical seawater by a factor of two. NaCl and HCO_3 predominant in the composition of the brine. Enrichment with the HCO_3 anion may indicate on-going processes of sulfate reduction. Elevated concentrations of metals,

including iron, zinc, manganese, cobalt, nickel, and copper, were also found within the composition of the brine. The origin of the sand remains puzzling. An source has yet to be found in this part of the Ionian Sea. The presence of a large quantity of rock fragments in the sand suggests that the sand was not associated with drift from the Nile River. From the side of the Island of Crete, the region under consideration is screened by the Pliny abyssal trench with depths exceeding 3300 m. It is still assumed that the sands and other deposits exposed at the tops of domes are fairly old formations and that their sediments accumulated prior to the formation of the Hellenic trench system. The fact that the sediments being described lie on the seafloor at present probably indicates active fold formation in a zone of very close juxtaposition of the African plate with the Aegean volcanic arc, as a result of which, Recent carbonate and Holocene sapropel muds did not accumulate on the crests of uplifted folds. Moreover, Pliocene-Quaternary formations, ubiquitous in the Ionian Sea and exhibiting a predominantly carbonate composition, are absent here. The age of sand now accumulating on the surfaces of domes in the northern part of the Eastern-Mediterranean Ridge is probably Late Messinian or Tortonian, but may be older.

GEODYNAMIC ASPECTS OF PROCESSES TAKING PLACE IN THE DEPTHS OF SEDIMENTARY BASINS IN THE COLLISION ZONE

Thus, diverse phenomena occur in the vicinity of a collision of ancient continental margin with volcanic island arc (arcs). These processes transform the sedimentary cover of sedimentation basins to a substantial degree: from diapirism and mud volcanism to the formation of diverse, primarily small folds evidently complicating larger structures. The presence of brines, which are enriched with metals, hydrocarbonate ions, and hydrogen sulfide in mud-cone clays and other sediments found on the arches of certain rises suggests a deep-seated origin for fluids rising to the surface. Hydrocarbon phases probably play an important role in their composition. This is indicated by the activity of microorganisms, numerous colonies of which are found in Recent sediments overlapping domes [11]. All of this indicates broad-scale redistribution of fluids and the presence of hydrocarbons in fluid compositions from the lower or intermediate stages of the sedimentary cover to the upper stages, a redistribution which is accompanied by breakdown of old oil and gas pools and formation of new ones. The presence of sands possibly serving as reservoirs suggests that large zones of oil and gas accumulation may occur at depth in the abyssal part of the Ionian Sea.

It is impossible to rule out the possibility that the consolidated sands on the crests of domes south of Pliny trench are due to the phenomenon of sand diapirism described by Kholodov using Cheleken Peninsula as an example [8]. If this proves to be true, sandy material brought up from great depths may be much older than presently assumed. Actually, during one of the first surveys of mud volcanism in the Mediterranean Sea, a Cretaceous age was tentatively suggested for mud-cone clays raised up from the top of the first mud volcano discovered in the vicinity of the Eastern Mediterranean Ridge [10]. Consequently, there is controversy concerning the subsalt pre-Messinian sedimentary complex.

As mentioned earlier, petroclastic material with fragments of sedimentary and metasedimentary rock predominating play a substantial role in the composition of "mud-cone" clays. This indicates short transport routes, since the majority of petroclasts are usually broken down during long transport (by large rivers, for example). Probably, the ancient source area for clastic terrigenous material was located close by, possibly in the vicinity of the island of Crete or the Ptolemy rise, now under water. Most likely, there will be continued controversy concerning the presence of foreshore or shallow water-shelf sandy deposits in spatial proximity to a section with siltstones and clays.

Taken as a whole, the facts presented allow us to assume that this area, the northern part of the basin of the Ionian Sea, is a part of the deeply subsided African plate, once the margin of Gondwana in the Mesozoic Tethys Ocean. We have good information concerning which sedimentary complexes compose this margin in neighboring, more easterly sectors, for example, in the vicinity of Persian Gulf. Here, widely distributed terrigenous sandstones of Early Cretaceous age, along with reef structures of the Aptian-Albian and Late Cretaceous as well as Late Jurassic sulfate-carbonate lagoonal complexes, play an important role as a regional reservoir within the margin of the Arabian shield. We do not rule out the possibility that formations of similar composition and age are present at depth within the Ionian Sea; such formations would substantially enhance prospects for oil and gas in the area.

Paleogeographic and palinspastic reconstructions carried out in recent years [2] indicate that the Arabian margin of Gondwana at the end of the Mesozoic-first half of the Cenozoic was situated in a collision zone with a volcanic island arc once bordering the southern margin of Eurasia in the Tethys Ocean, i.e., it was once in the same situation which the

African margin in the eastern sector of the Mediterranean Sea is now in. Consequently, it can be assumed that similar processes took place there.

Subsequently, the volcanic arc lost its activity and, in the end, closed up with the old margin of the Eurasian continent, gradually merging with the African–Arabian megablock. During the Maastrichtian, obduction of fragments of Tethys oceanic crust onto the margin of the Arabian shield took place in the collision zone, with the Oman ophiolite complex forming as a result. Subsequently, even into the Eocene and Oligocene, collision took place over a broad strip now known as the Zagros zone. The collision was probably of a "soft" character and was unaccompanied by crumpling and denudation of the sedimentary cover within the Arabian margin. It resulted in the formation of anticlinal folds and diapirism of Lower Paleozoic salts (local in character, however). Nonetheless, it is undoubtedly true that collision processes initiated generation of bitumoids and large-scale redistribution of fluids, which migrated from complexes subjected to compression and destruction in the Zagros zone. Traps formed in the sedimentary cover during the approach and collision of the two plates were filled with these fluids. It is evident that tectonic transformations which took place in the Persian Gulf at the Mesozoic–Cenozoic transition later distinctly facilitated the creation of a large-scale oil and gas basin here, with reserves of more than 54 billion tons of oil and 20 trillion m³ of gas [1].

The Gulf of Mexico, associated with one of the largest oil and gas basins of modern times, is another large region with a collision episode involving a continental margin and a volcanic island arc in its history. The convergence and subsequent collision between the margin of the North American continent and the Greater Antilles island arc took place at the end of the Jurassic – beginning of the Cretaceous. A number of important criteria indicate that this basin is presently very similar to the Ionian basin: depth to the seafloor does not exceed 2000–3000 m; fairly thick salt caps are present in the upper parts of the sedimentary cover (the salts here are of Late Jurassic age); there has been long-term formation of deltaic and submarine-deltaic complexes within the continental margin (in this case complexes of the Mississippi River and, in the case of the Ionian Sea, an equivalent deltaic complex and alluvial fan of the Nile River); in both cases, there are regional manifestations of salt diapirism and mud volcanism. Finally, let us note the accumulative, lowland type of coast with a chain of salinized lagoons, the largest of which being the Madre lagoon. The structure of the African coast bordering the Ionian Sea is similar. Proven resources of hydrocarbon raw materials in the basin of the Gulf of Mexico total approximately 6 billion tons of oil and more than 2 trillion m³ of gas [1].

Yet another region in the eastern hemisphere where collision processes have unfolded during recent geological epochs is the Australian–Indonesian segment, where the northern margin of Australia collided with the arc of the Banda Sea, in other words, the Timor volcanic arc. These processes were accompanied by salt diapirism (Silurian–Devonian in this case) and formation of large arched uplifts (Epemer-Sakhul, Sakhul, and Nortist-Londonderry). Discoveries of oil and gas pools in this region are associated with such structures.

It is important to note that some of the evidence of tectonic events in the distant geological past is controversial. The collision between the margin of the Eastern European platform and the Sakmara volcanic arc, which belongs to the end of the Carboniferous–beginning of the Permian, has been fairly well reconstructed. As is well known, numerous oil and gas deposits including very large deposits, have been discovered in neighboring regions of the Volga-Urals and Caspian basins. This entire zone continues to be one of the most prospective in the central sector of Eurasia.

* * *

The data presented allows us to conclude that the conditions which arise as a result of soft collision between the passive margin of a continent and a volcanic island arc are very favorable for formation of large oil and gas basins in the collision zone. This is a consequence of the creation of numerous structural traps, due both to slight dislocations intrusive sedimentary covers of basins and active migration of fluids, including hydrocarbons, from the lower stages of the sedimentary cover to the upper stages; the majority of structural and nonstructural traps are filled as a result. It is important that not only basins of ancient passive margins located in the immediate collision zone, but also relic basins situated to the rear of the volcanic island arc during stages of creation and evolution of the volcanic island arc are highly prospective for oil and gas.

LITERATURE CITED

1. A. A. Geodekyan, A. Zabanbark, and A. I. Konyukhov, Tectonic and Lithological Problems of Oil and Gas Content at Continental Margins [in Russian], Nauka, Moscow (1988).
2. L. P. Zonenshayn, Zh. Derkur, V. G. Kaz'min, et al., The History of the Tethys Ocean [Russian translation], Mir, Moscow (1987).
3. A. I. Konyukhov, M. K. Ivanov, and A. V. Kalinin, "Geological structure and sedimentation features on the Black-Sea margin of the Caucasus," Vestn. Mosk. Gos. Univ., Ser. Geol., No. 6, 26-35 (1990).
4. A. I. Konyukhov, M. K. Ivanov, and L. M. Kul'nitskiy, "Mud volcanoes and gas hydrates in deep-water regions of the Black Sea," Litol. Polezn. Iskop., No. 6, 41-52 (1991).
5. A. I. Konyukhov, Yu.K. Burlin, and G. L. Chochiya, "Structure and sediments of the Messinian deep-water alluvial fan," Vestn. Mosk. Gos. Univ., Ser. Geol., No. 6, 41-52 (1991).
6. D. A. Tugolesov, A. S. Gorshkov, L. B. Meysner, et al., Tectonics of Mesozoic–Cenozoic Deposits of the Black-Sea Basin [in Russian], Nedra, Moscow (1985).
7. A. A. Terekhov and K. M. Shimkus, "Young sediments and thrust structures in the Crimean and Caucasus zones of the Black-Sea basins," Geotektonika, No. 1, 21-32 (1989).
8. V. N. Kholodov, "The role of sand diapirism in the development of mud volcanoes," Litol. Polezn. Iskop., No. 4, 12-27 (1987).
9. A. Castellaria and R. Sartori, "Quaternary iron–manganese deposits and associated pelagic sediments from the Tyrrhenian Sea," Sedimentology, **25**, No. 6, 35-42 (1978).
10. M. V. Cita, W. F. Ryan, and L. Paggi, "Prometheus mud-breccia. An example of shale diapirism in the Western Mediterranean ridge," Ann. Geol. Pays Hellen., **30**, 543-570 (1981).
11. M. V. Cita, F. S. Aghib, S. Arosio, et al., "Bacterial colonies and Mn-micronodules related to fluid escape on the crest of the Mediterranean ridge," Riv. Itol. Paleontol. Strat., **95**, No. 3, 315-336 (1989).
12. F. Fanucci, M. Firpo, M. Picazzo, et al., "Morphostructural features and evolution of the Ligurian Sea," Miscellanea, **4**, 29-44 (1992).
13. T. Marjanač, "Ponded megabeds and some characteristics of the Eocene Adriatic basin (Middle Dalmatia, Yugoslavia)," Mam. Soc. Geol. Ital., **40**, 241-249 (1987).
14. J. Obradović, P. Stoyadinović, B. Mizcović, et al., "Adriatic carbonate platforms and their characteristics as seen in the Montenegro littoral," Glasnik prirodnjackog muzeja u Beogradu, A **4041**, 81-85 (1985-1986).
15. E. Saccani, "Double provenance of sand-sized sediments in the Southern Aegean forearc basin," J. Sediment. Petrol., **57**, 736-745 (1987).

THE SALOP-GILLULY CURVE. REALITY OR ARTIFACT?

V. N. Kholodov

UDC 551.461.8:551.14

In the article, we analyze the sedimentation rate curve and its variations over the Earth's history. We show the necessity for distinguishing between sediment deposition rate and sediment burial rate in present-day sedimentary basins. In ancient sedimentary and volcanogenic-sedimentary strata, decreases in thickness have taken place as a result of compaction, loss of material, diapirism, and plastic deformations. As a result, we must consider not only sedimentation rate, but with thickness divided by time or rate of sedimentary rock formation as well. A methodology for reconstructing sedimentation rates is proposed.

Sedimentation rates of present-day sedimentary processes and sedimentation rates in the geological past are of enormous interest. Sedimentation rates are linked to questions concerning the evolution of topography on our planet, the evolution of distributive provinces and sedimentation basins, the evolution of compensated and uncompensated sedimentation, facies formation, formation of ore deposits, and growth and degradation of tectonic structures of various orders. Without exaggeration, it can be said that this problem touches upon a number of issues in lithology, stratigraphy, and tectonics.

This problem is far from resolved, despite numerous investigations by Holms [86], Umbgrove [97], Gilluly [83], Shatskiy [74], Key [15], Rukhin [44], Strakhov [55], Keller [16], Salop [46], Raaben [40], Lisitsyn [26, 27], Semikarov [49], Ronov [43], and Seslavinskiy [50-53].

Two main factors impede resolution of the problem. Above all, adequate estimates of present-day sedimentation rates in seas and oceans have been lacking for a long time. A few reports [4, 45, 87, 88, 91, 92] obscure or inaccurately portray the matter.

Secondly, geologists have shown a very hazy understanding of scales of secondary (diapiric and catagenetic) transformations of sediments and sedimentary rock and do not clearly appreciate how ephemeral thicknesses of sedimentary strata can be. It has been assumed that certain minor corrections (for rate of erosion, gravitational compaction of rock during burial, folding, and metamorphism) would allow reconstruction of thickness formed in an original sedimentation basin.

This approach has proved illusory. At present, we have a greater capacity to understand the complexity involved in reconstructing initial depositional environments and, consequently, initial thicknesses.

According to current thinking, sedimentation rate equals the thickness of sediment divided by the time taken for its formation. The Salop curve [46] (Fig. 1) describes overall variational trends in thickness of sedimentary and volcanogenic-sedimentary deposits of the lithosphere over time.

According to the graph shown (a graph, incidentally, based upon Gilluly's data, particularly where Phanerozoic deposits are concerned), average thicknesses of deposits gradually decrease from younger to older formations, since the corresponding intervals of geological time increase from tens of millions to millions and billions of years.

A question naturally arises, as put forward in the reports of Gilluly [83] and Raaben [40]: might the entire curve be an artifact, might it be constructed on the basis of systematic errors in measuring thickness?

It should be immediately emphasized that the incompleteness of the geological record is undoubtedly very great and, for the most part, becomes progressively greater from younger deposits to older ones [40, 56, 74, 83]. This fact makes comparative lithological construction very tentative and outside the realm of precise laws.

However, this incompleteness faces geologists when they are determining thicknesses of ancient deposits by summing separate "individual" measurements and providing overall, statistically derived estimates of thickness of stratigraphic units. In this connection, Gilluly's assertion [83] that the approach to estimating thicknesses in the Precambrian is one-sided should raise some questions.

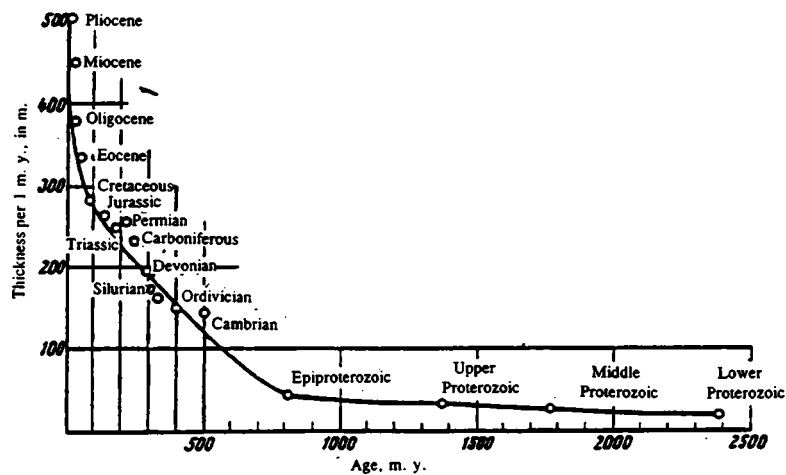


Fig. 1. Relationship between thickness of sedimentary deposits and times taken for the formation.

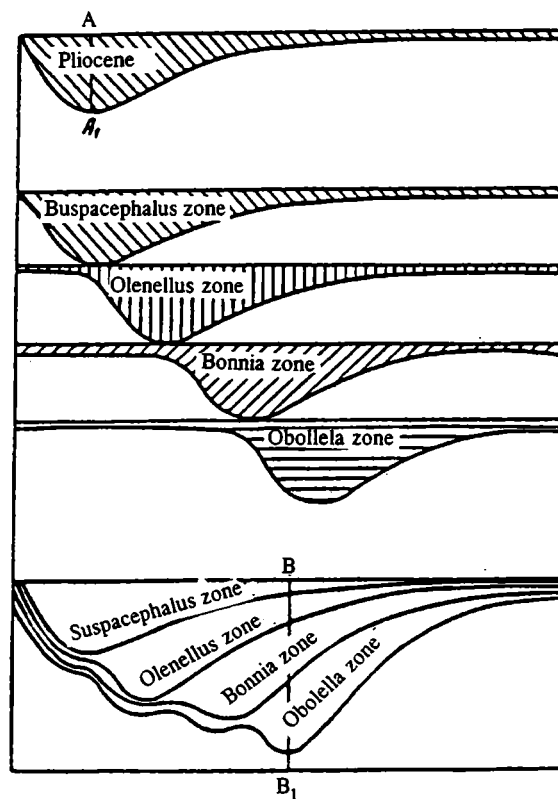


Fig. 2. Diagram illustrating proposed systematic error associated with thickness in the Precambrian [83].

Let us keep in mind that Gilluly attempted to prove that measurements of thicknesses of sedimentary strata in ancient deposits can always be carried out according to the scheme shown in Fig. 2. He emphasized that the final result is diminished if a multitude of individual measurements are replaced by a single, overall measure.

Above all, it should be emphasized that patterns of formation of thicknesses and depocenter shifts are closely linked to the type of sedimentary basin involved: these patterns are different in intracratonic, epicratonic, trough-type, rift-related, and oceanic paleobasins [42, 48]. From the position of current lithology, the situation considered by Gilluly [83] can therefore hardly be considered unique and typical of the entire Precambrian.

TABLE 1. Rates of Present-Day Sedimentation [26-28]

Sedimentation basin	Sedimentation rate, cm/1000 years
Oceans	
<i>Pacific:</i>	
with respect to deepwater sediments	0.1-10
shelf of the Gulf of California	20-316
mouth of the Menam River	3000
<i>Indian:</i>	
with respect to deepwater sediments	0.1-10
mouth of the Greater Godavari River	100-300
mouth of the Irvadi River	200
shelf of Hindustan	10->100
Seas	
<i>Atlantic:</i>	
with respect to abyssal sediments	0.1-10
mouth of the Potomac River, Chesapeake Bay	160-1800
mouth of the Parka River	1000
mouth of the Mississippi River	1000
mouth of the Orinoko River	500-1000
shelf of Europe	100-600
<i>Mediterranean</i>	3-20
mouth of the Rhone	500-600
<i>Azov</i>	90-240
<i>Caspian</i>	10-600
<i>Baltic</i>	240
<i>Andaman</i>	10-200
<i>Bering</i>	5-50
<i>Okhotsk</i>	2.5-50
<i>Black</i>	2-40
<i>Arabian</i>	0.1-0.5
<i>Red</i>	0.1-0.3

In principle, moreover, frequent use of "local" measurements of thickness in Precambrian sections does not result in systematic error. In this connection, we propose that the pattern shown in Fig. 1 objectively describes naturally-occurring relationships, but requires a somewhat different interpretation.

An analysis of the problem should begin with a consideration of recent sedimentation rates. In a number of previous reports [45, 55], it has been asserted that sedimentation rates in recent bodies of water are negligibly small and ranges from several millimeters to several centimeters per thousand years and approximately corresponding to rates of sediment accumulation in water bodies of the past.

Patterns of behavior of recent sedimentation rates in seas and oceans have been thoroughly investigated by Lisitsyn [26-28]. Using biostratigraphic, paleomagnetic, and lithological methods, and well as methods of nuclear geochronology, this investigator picked an interval of 300-700 thousand years and traced it over the Pacific, Atlantic, and Indian ocean floors as well as over the floors of a number of adjoining seas. On the basis of more than 700 individual measurements, he compiled a map of distribution of sedimentation rates. Summary results of his observations are shown in Table 1. It should be kept in mind that the numbers presented were rechecked by means of the method of absolute weights. After analyzing the data in Table 1, it is difficult not to arrive at the same conclusion reached by Lisitsyn [26-28]: against the background of fairly low sedimentation rates typical of relatively deep-water areas of the ocean and the higher sedimentation rates found in both seas which are not land-locked and epeiric seas, there are regions where sedimentation rates reach "avalanche" or "hurricane" values.

Whereas the average sedimentation rate during the Pliocene can be approximated as 4 m/1000 years (see Fig. 1), the rate of current sedimentation on ocean shelves exceeds 30 m/1000 years at the mouth of the Menam River, exceeds 10 m/1000 years at the Mississippi and Paris river deltas, and exceeds 5 m/1000 years in the zones of influence of the Orinoko and Rhone rivers.

TABLE 2. Properties of Sediments and Sedimentary Rocks

Clayey mud	Natural humidity, %	Porosity, %	Density, g/cm ³	Consistency
Clayey mud	80—75	80—75	0,6—0,8	Liquid, viscous
Clay: soft	80—30	80—40	0,8—1,4	Flowing, plastic
compacted	35—12	45—25	1,35—1,90	Plastic, semi-solid
Mudstone	15—3	30—4	1,90—2,65	Semi-solid
Slate-like mudstone	4—3	5—4	2,65—2,75	Solid

The entire shelf region under the influence of deltas and estuaries of large rivers is considered by Lisitsyn [28] to be the first global level of avalanche sedimentation; here, there are local concentrations of huge masses of water-encroached sand, sandstone, siltstone, and clay, which play roles in slide and suspension migration and also slide along the continental slope to form second-order gravitite sediments at the foot during strong fluctuations in sea level.

A more detailed description of the entire path of avalanche sedimentation at the ocean periphery is presented in the reports of Lisitsyn [26-28]; therefore, we will only note here that, in addition to areas with maximum sedimentation rates, zones of zero sedimentation (non-deposition of sediments) and zones of erosion of previously deposited sediments are widely occurring in present-day sedimentary basins. The latter, as pointed out by Bezrukov [3], Lisitsyn [28], Murdmaa [34], Sval'nov [45] and others, are widespread even among very deep-water deposits of the ocean; their formation is usually associated with the activity of submarine currents.

Since marked redistribution of material takes place from time to time, both between different levels of avalanche sedimentation and between areas of sediment accumulation and erosion, the following becomes evident: the sedimentation rates shown in Table 1 are insufficient for complete characterization of the pattern as a whole. In a geological analysis, they should be supplemented with burial rates of marine and oceanic sediments, and these latter rates should probably be substantially lower than hurricane values. This is confirmed by an analysis of deep-sea drilling data. As demonstrated by Davis et al. [81] as well as Worsley and Davis [98], rates in sedimentary strata underlying Quaternary deposits are substantially less than the numbers presented.

It is easy to see that the very mechanism of recent sedimentation in seas and oceans extremely complicates quantitative geological estimation; we can easily visualize rate of sediment deposition, but are still far from a precise estimate of sediment burial rate. In the meantime, we are often faced with the final result in sections of the geological past, i. e., with sediments finally buried under a mass of latter deposits.

It should also be noted that the most recent lithologist-directed investigations of seas and oceans have led to the opinion that hidden gaps play an especially important role in the structure of ancient sedimentary strata.

Just as deep a methodological precipice separates sediments finally deposited on the bottom but encroached upon by water from completely formed sedimentary rock, sometimes even compressed into folds and slightly metamorphosed. Along the pathway of sediment conversion to rock, sediment thicknesses are strongly deformed under the influence of compaction, losses of substantial portions of active components, plastic deformations, and diapiric phenomena.

Compaction of sediments and sedimentary rocks of various lithological compositions has been described in the reports of Bassoyevich [6], Ueller [58], Engel'gardt [76], Mukhin [35], Logvinenko [29], Ricke and Chilingarian [89], Khanin [60], Kholodov [66] and others.

During the formation of marine sedimentary strata, each bed begins its development with sediment deposition at the bottom of a body of water; the bed is then covered by younger sediments which progressively increase in thickness as burial continues uninterruptedly. This process can be visualized as a slow descent into the depths of the Earth's crust. Geostatic pressure and temperature continuously increase during this process according to the following pattern: 1 km, 30°C and 270-300 atm; 2 km, 60°C and 540-600 atm; 3 km, 90°C and 810-900 atm, etc. Hence, the density of the rock also progressively increases with burial, whereas the porosity shows a corresponding decrease.

The behavior of clay rock in this process was experimentally investigated by Lomtadze [30] based upon the data presented in Table 2. He showed that clayey mud with a density of 0.6-0.8 g/cm³ and a moisture content of 75-80% is transformed under the influence of increasing pressure and temperature to a slate-like mudstone with a density of 2.65-2.75 g/cm³ and a humidity of 3-4%.

TABLE 3. Density of Sedimentary Rock (g/cm^3) of Various Tectonic Zones in the West of Central Asia (according to [10], S. M. Vilenskiy and I. Kh. Yudborovskiy)

Age	Fold region	Transitional zone	Stable zone
Paleogene	2,29	2,25	1,87
Senomian	2,52	2,43	2,16
Senomanian	2,47	2,28	2,00
Albian	2,49	2,41	2,05
Aptian	2,56	2,59	2,14
Neocomian	2,64	2,53	2,20
Jurassic	2,64	2,56	2,35

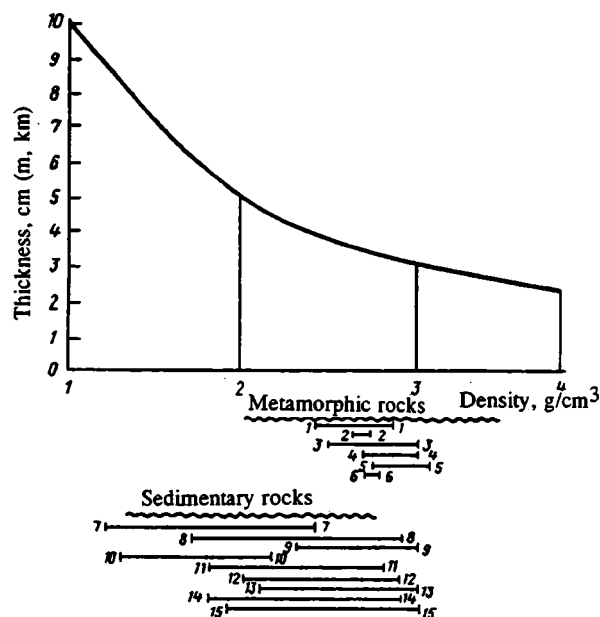


Fig. 3. Relation between density of sedimentary and sedimentary-metamorphic deposits and their thicknesses. Variations in density: 1-3) schist (1: quartz-sericite, 2: chlorite; 3) graphite-amphibolite); 4) gneiss; 5) amphibolite; 6) marble; 7) clay; 8) mudstone; 9) clay shale; 10) sand; 11) sandstone; 13) conglomerate; 14) limestone; 15) dolomite.

The density of clayey muds, according to data gathered by Dortman et al. [10] and more recent determinations by Lisitsyn [27], ranges from 1.2 to 2.4 g/cm^3 ; the density of mudstone ranges from 1.7 to 2.9 g/cm^3 ; the density of clay shale ranges from 2.3 to 3 g/cm^3 .

In contrast to clayey rocks, sands have densities of 1.3-2.15 g/cm^3 and cemented sandstones have densities of 2-2.9 g/cm^3 . It is curious that the density of terrigenous rock usually increases with grain size; densities of conglomerates range from 2.1 to 3 g/cm^3 .

In the majority of cases, carbonate rocks have higher densities than terrigenous-clayey deposits. Actually, densities of limestones range from 1.8 to 2.9 g/cm^3 ; densities of dolomites range from 1.9 to 3 g/cm^3 .

It stands to reason that metamorphism increases sediment density even more; densities of quartz-sericite schists range from 2.4-2.87; densities of gneisses range from 2.76-3.0 g/cm^3 ; and densities of amphibolites range from 2.72 to 3.04 [10].

Together with lithological composition, dimensions of fragments, and the mineralogical characteristics of fragments, the age of the rock and intensity of tectonic processes play an important role in the creation of density. Table 3 shows data allowing us to assess the behavior of sedimentary rocks in Jurassic, Cretaceous, and Paleogene deposits of Central Asia. They do not indicate that densities of noncoeval rocks everywhere increase from top to bottom along the

stratigraphic column, from Paleogene to Jurassic. These numbers definitely confirm the theoretical models of Lomtadze [30] and other investigators concerning compaction sediments and sedimentary rock during burial.

It is curious that effusive rocks undergo identical alterations. As described by Dortman, Trunin, and Khorev [10], Cenozoic basalts of the Urals and a number of other regions show densities of 2.38-2.74 g/cm³, Mesozoic show densities of 2.59-2.75 g/cm³, and Paleozoic rocks show densities of 2.46-2.85 g/cm³. Differences in densities of sedimentary rocks of fold and platform regions are also evident in Table 3; it is apparent that fold regions are characterized by higher densities than those found in platform regions.

The total quantitative effect of compaction of the thickness of sedimentary strata is shown in Fig. 3. The diagram is constructed for variations in density ranging from 1 to 4 g/cm³; these are the most abundant values in the lithosphere. In the lower part of the figure, segments running parallel to the abscissa characterize density variations for different types of sedimentary and metamorphic rock; they are taken from a handbook. Along the ordinate, we have attempted to estimate reduction in thickness in terms of 10 arbitrary units (cm, m, km) during compaction of a rock column from 1 to 4 g/cm³. It is apparent that only 50% of the original thickness remains for a density of 2 g/cm³, 33% remains for 3 g/cm³; and 25% remains for 4 g/cm³. In other words, thickness is initially reduced two-fold, then by 1/3 of the original value, and then by 3/4.

Reductions in thicknesses of sedimentary and volcanogenic-sedimentary rocks over the course of diagenetic and catagenetic transformations intensify loss of various components, including water, organic matter, carbonates, and other easily dissolved salts and unstable silicate minerals.

In some cases, these mineral-geochemical transformations are directed linked to compaction of parental sediments and sedimentary rock; even density may reflect this process. In other cases, the geophysical density remains constant, but material losses strongly indicate decreased thickness due to removal of individual layers, whole portions of the framework and cement, and even the creation of ephemeral cavities, pores, and caverns.

The behavior of water during diagenetic and catagenetic transformations of clay, sandstone, and carbonate rock has been repeatedly discussed in the reports of L. M. Ovchinnikov, A. A. Kartsev, E. A. Baskov, S. V. Vagin, I. I. Nesterov, V. F. Linetskiy, Dzh. Ueller, V. M. Dobrynin, and many other investigators.

The behavior of water during compaction of clays has been most thoroughly studied. Water trapped in clay occurs either in the form of pore solution ("free") or in a bound state (sorbed or crystallization water).

Pore solutions are the first to be removed from compacting clays; in this case, reduction of pore space and loss of thickness are directly related [6, 37, 85] and can be computed by means of appropriate formulas. This first stage of dehydration, or stage of initial compaction of clay, is accompanied by fairly substantial water loss, with water loss taking place more or less uniformly and gradually decreasing with reduction in total pore volume. Intensification or weakening of this process is controlled by the rate of overburden accumulation, which, in turn, depends upon many physical-geographic factors. Typically, all clay deposits of marine origin, regardless of their mineral composition, pass through a stage of dehydration.

According to our rough calculations, 1 m³ of mud loses 370-380 kg of water during this dewatering stage.

The second stage of dehydration, or the stage of mechanical dehydration, is associated with the conversion of the swelling montmorillonite predominating in the zone of weathering to non-swelling hydromica, a consistent component of deeper zones. This typically takes place at high (150-200°C) temperatures at depths of 1-4 km and is accompanied by decrease in the volume of solid phase and liberation of a substantial quantity of crystallization water. Calculations indicate that 1 m³ of pure manganese clay can release 280-300 kg water, with 190-200 kg water retained in 1 m³ of the newly formed hydromicaceous mass.

During this stage, the transformed thickness of clay deposits decreases according to complex laws and, in a number of cases, the deficit exceeds the change in pore space [37].

During subsequent transformation of clay deposits into zeolite, phrenite-pumpellite, glaucophane-schist, and eclogite facies, alternation of fluidization and dehydration episodes proceed against a background of continuous decrease in density; the overall effect of these processes results in a 25-50% decrease in thickness [59].

Conversions of organic matter have an especially important effect on thickness reduction of sedimentary deposits. "Melting" of organic accumulations in the lithosphere can be clearly traced, both among coals and among saproplanktonogenic clays and shales.

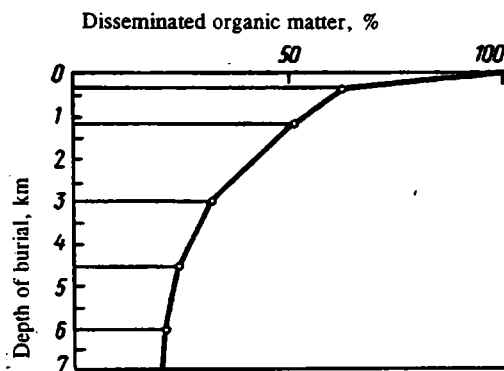


Fig. 4. Decrease in content of disseminated organic matter (DOM) in clays with deep burial.

Two processes proceed in parallel in coals. Marked compaction, dehydration, and gradual conversion of peat into brown, long-flame, gas, fat, coking, lean-baking, and lean coals and anthracites take place during peat formation and coalification. Together with these phenomena, oxygen exerts a direct effect upon the coal mass according to the formula: $C_6H_{16}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{heat}$. A substantial portion of the original plant organic material is completely destroyed during this process. As a result, according to the data of Schwartz and Laupper [75], coal under pressure reduces its mass by a factor of 12-30; Zhemchuzhnikov [12] estimates this loss to be 10-12 fold.

Direct measurements of the coefficient of compaction in Jurassic coals on the eastern slopes of the Urals, carried out by Chernousov [72], confirm Zhemchuzhnikov's hypothesis: it turns out that the oblateness of tree trunks and knots in wood is 1:12.

Black clays and shales rich in saproplanktogenic materials are, in essence, just as markedly reduced in thickness during stages of diagenesis and catagenesis. The transformation of disseminated organic matter (DOM) was discussed in detail by the authors in a number of previous reports [65-70].

It has been shown that saproplanktogenic material buried in semi-liquid clayey muds of marine basins are first rapidly consumed by biogenic sulfate production. In the opinion of Strakhov [55] up to 32% (according to the data of O. K. Bordovskiy more than 42%) of the initially buried mass of DOM is utilized during oxidation of C_{org} and reduction of sulfates to sulfides. In this process, the principal constituents of DOM (proteins, fats, and carbohydrates) are converted under the influence of diverse bacteria into humic acids and melanoids.

Further conversions of DOM take place in the zone of catagenesis, under the influence of its high temperatures and pressures. As a result of thermolysis and thermocatalysis, kerogen is initially formed from humic acids. (Kerogen is a three-dimensional molecule consisting of rings of organic heterocyclics joined by aliphatic ketone, ester, sulfide, and disulfide bridges.) Then, liquid and gaseous hydrocarbons and bitumoids are created from kerogen as a result of breakage of connecting chains during the principal phase of oil formation.

These neoformations migrate beyond the oil sourcebeds, but a strongly coalified mixture of relics of kerogen material remain in the sourcebeds.

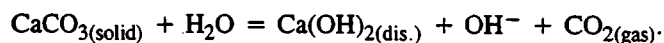
It is curious that, according to the data of Neruchev et al [36] and Akramkhodzhaev [1], losses of organic matter in oil sourcebeds appear just as shown in Fig. 4. In other words, only 32% of initially buried DOM remains after burial of oil source deposits to a depth of 3 km; only 21% remains after burial to a depth of 7 km.

Direct determinations of coefficients of compaction confirm that quite appreciable consumption of DOM and intensive compaction of black clay takes place during diagenesis. A comparison of thicknesses of layers inside and outside carbonate concretions, carried out by Gavrilov [8] indicates that thicknesses of such layers are reduced 6-7 fold only during this early stage of transformation.

Postsedimentary reduction in thickness is, to a substantial degree, caused by dissolution of carbonates, as well as reworking of DOM. When considering these phenomena, one should always keep in mind that disseminated carbonates can occur among clays, sandstones, schists, phosphorites, and siliceous rocks; in addition, they can form separate accumulations in the form of beds, lenses, and lenticular bodies.

The behavior of carbonates during post-sedimentary transformation depends, to a significant degree, upon the permeability of the enclosing rock. In cases involving an open physical-chemical system in which the carbon dioxide generated can freely escape, a situation favorable to dissolution and collapse of carbonate minerals is created.

In a series of reports, Kissin and Pakhomov [17, 18] actually showed that carbonate hydrolyzes with distilled water during heating from 75 to 120° C at gas-saturation pressure according to the following scheme:



In other words, pores, caverns, stylolite joints, sutures, and fissures reflecting dissolution and removal of carbonate material can appear in rock as a result of hydrolysis.

It is interesting to note that different carbonate minerals hydrolyze at different temperatures; siderite hydrolyzes first, followed by magnesite and dolomite and, finally, calcite.

The results of laboratory experiments carried out by Kissin and Pakhomov [17, 18] confirm the importance of a number of phenomena. These same authors demonstrated that the quantity of carbon dioxide gas CO_2 in Tertiary reservoirs of the Cis-Caucasus is closely related to formation temperature; there is a direct relationship between these factors in the temperature interval 75-150°C.

According to data presented by Minskiy [33], Proshlyakov and Gal'yanova [39], and also Vol'fson and Minskiy [7], the porosity of carbonate reservoirs in different oil and gas provinces of world predictably decreases with depth; in the depth interval of 1.5-2.5 km, however, this pattern is disrupted and a zone with optimal reservoir properties typically forms. In such a zone, overall porosity increases to 13-32%. It is easy to explain this deviation as due to hydrolysis of carbonates when the temperature increases.

It should be emphasized, however, that dissolution of carbonate minerals does not always accompany burial at depth in a sedimentary basin. Reports in the USSR [31, 61] and a number of reports by a number of foreign investigators have shown that carbonates are stable over a wide range of temperature and pressure when the environment in the sedimentary basin is closed physical-chemical system.

Nevertheless, dissolution of carbonate minerals in zones of diagenesis and catagenesis takes place fairly often; it is precisely this which, according to Stockdale [94-96], Blake and Roy [78], Rigby [90], Uspenskiy [57], Dunnington [84], Kholodov [62], Gushinskiy [5], Maslov [32], Goldyrev and Kuznetsov [9], and Plakhotniy [38], results in formation of stylolite joints, sutures, and suturelike structures, which, in turn, cause substantial reductions in thicknesses of carbonate strata.

According to Stockdale [96], development of stylolite jointing usually decreases the thickness of a carbonate deposit by approximately 40%. A more precise estimate of stylolitization associated with faults was carried out Bakun [21]. His data suggest that Jurassic bituminous limestone of the Chelgar anticline (Tadzhikistan) after undergoing stylolitization near a complicating fault structure, was reduced in thickness by 17-23%.

Similar results were obtained by Bodo [79], after making a detailed study of the amplitude and frequency of occurrence of stylolite joints in the Upper Jurassic limestones of Burgundy. According to the data of this investigator, relatively homogeneous and dense limestones loss ~12% of their thickness as a result of dissolution under pressure, whereas less dense varieties with intricate patterns of porosity undergo a 21% reduction in thickness during stylolitization.

In terrigenous rocks, sandstones and siltstones, framework compaction is usually also accompanied by dissolution under pressure. As well demonstrated by Sloss and Feray [93], Byrma and Riley [80], and, especially Heald [84] and Koneliovich [19, 21], compaction of terrigenous rock during burial to depths of 1.5-4.0 km involves the formation of microstylolitic, conformal, or incorporational structures, on the one hand, and dissolution of unstable minerals, on the other.

Without special microscopic observations and paragenetic analysis, it is very difficult to assess the quantitative influence of these processes on thicknesses of sedimentary deposits. Kopeliovich [20], after thoroughly investigating these phenomena in Riphean strata of the southwestern Russian platform, arrived at the conclusion that the cross-sectional areas of grains in coarse-grained sandstones is now 98-95% of initial cross-sectional areas, whereas cross-sectional areas of grains decreased to 97-90% of original values in fine-grained sandstones and siltstones. This investigator estimates that the corresponding quantity of material dissolved during this process, taking "collapsed minerals" into consideration, is a few tens of percents.

Phenomena of "hydrovolcanism" [14], "sand diapirism" [63, 64], and mud volcanism exert a very substantial influences on the thickness of sedimentary strata. It is now believed that these processes are not unusual, but rather constitute a definite stage in the development of any sedimentary-rock basin [54].

As a result of the creation of zones of anomalously high formation pressure during the stage of catagenesis, fluidization and "melting" processes take place in contiguous reservoirs-beds, ending in hydraulic rupture of beds or hydraulic penetration of a melted mass to the day surface. Clastic dikes, "beds with inclusions," and mud volcanos are formed.

Clastic dikes are large, unusual fissures in clay; they are filled with tightly cemented arenaceous material and are morphologically very similar to so-called neptune dikes. In some cases, they cross-cut the bedding of the enclosing clay, whereas, in other cases, they are conformable with the bedding. Dikes frequently form a network surrounding normally bedded layers of sandstone, turning upward and downward from the sandstone layers. The intricate shapes of clastic dikes, their fairly large dimensions, the persistent presence of sharply angular fragments of enclosing clay among sandy grains, the widespread occurrence of siderite or sulfide cement among them, frequently impregnated with brown bitumoids, are striking. Dike walls which cross-cut bedding and upon which layers of the enclosing clay and sometimes diagenetic carbonate concretions lying within such layers, have been imprinted are very typical.

Horizons with inclusions include blocks, balls, or patches of sandy beds lying among deformed clay. Typically, such sandy inclusions occur in markedly varied shapes and sizes; they can be found between two completely undeformed sandstone beds, with the thicknesses of such horizons persisting for substantial distances. A number of gradual transitions can be found between clastic dikes and "horizons with inclusions."

Mud volcanos result from the eruption of a mass of mud-breccia or sandy melted material at the day surface. Morphologically, they are either cone-shaped rises reaching 1.7 km in cross-section and 0.4 km in height or collapsed craters. The "roots" of mud volcanos can descend to depths of 3-5 km. Their vents are clearly controlled by a system of faults, most often coinciding with the arch of an anticlinal rise. The crater areas of these structures are typically covered with numerous small salses and gryphons, through the channels of which clay solutions, sometimes with bitumoids, erupt, along with gas blowholes. Fairly long-lasting periods of gryphon-salse activity are interrupted from time to time by large-scale but brief eruptions of mud-breccia, fluids, and gases. There is a distinct rhythmicity in the activity of most mud volcanos. Clastic dikes can frequently be identified within the vents of old mud volcanos laid bare by erosion (Aligul and Boyadag, the volcanos of Turkmenia).

All these phenomena have substantial influences on the thicknesses of the initial sedimentary strata. The following figures provide some conception of the role of mud volcanism in the reduction of thickness of sedimentary deposits feeding into sedimentary strata.

In an atlas of the mud volcanos of Adzerbaydzhan [77], an attempt was made to estimate the volume of solid ejecta, mud breccia brought to the day surface over the course of eruptions from 75 volcanos. It should be emphasized that these data apply only to a volcano's one-time outburst creating a volcanogenic-sedimentary mantle, rather than to the entire edifice of the volcano. The total mass of mud breccia, especially at such giants as Tuoragay, Bol'shyy Kyanizadag, Malyy Kyanizadag, or Mishovdag, may substantially exceed the volumes presented.

The total volume of solid-ejecta products from the mud volcanos of Azerbaydzhan is estimated to be 54 km³. If we assume that the area over which these volcanos occur equals 4400 km², it is easy to conclude that the thickness of the parental deposits supplying the "roots" of volcanos should have decreased by 12 m. Keep in mind that this is a minimal estimate of reduction in thickness of sedimentary and volcanogenic-sedimentary deposits involved in the evolution of elisional systems.

The high plasticity of certain sedimentary rocks, including gypsum, anhydrite, salt, evaporites, and certain carbonate rocks, has a great effect upon the thickness of the sedimentary cover. In some cases, traces of plastic movements of evaporites can be found in platform troughs with no evidence of tectonic folding.

Mother brines trapped within evaporite strata show substantially higher electrical and heat conductivity than these formations and increase the plasticity of saline masses. In parts of old saline basins where evaporite formations reach substantial thicknesses (~1500-2000 m), salt tectonics is a widely occurring phenomenon: salt diapirs, stocks, and rises can form [11, 13, 23, 41].

Diapirism of saline deposits in some sedimentary-rock basins is a large-scale geological phenomenon. For example, upwards of 76 anticlinal rises with salt stocks in their cores were formed at the base of Devonian saline strata in the

Dneiper-Donets basin. Here, domes reach 30 km in cross-section and roots of domes extend to depths of 5-7 km. Crests, lenses, columnar stocks, and mushroom-shaped stocks can be distinguished.

In the gulf-coast region (USA), more than 100 salt domes have been investigated. Occasionally, rises sharply exceed 1.5-6.5 km in size. They are elliptical in plan and are covered by cap rock. These diapiric structures have roots in Jurassic or Pennsylvanian saline deposits [25, 41].

The causes of extrusion of salt masses and formation of diapirs are not yet fully explained. It is assumed that the following may play important roles in this process: 1) rate of dehydration and increase in density of sedimentary rocks overlying saliferous deposits; 2) brine and water content in saline formations; 3) composition, character, and thickness of evaporite beds; 4) temperature and pressure at depth of the salt-source suite; 5) tectonic stresses.

Khot'kov and Valukonis [71], propose that saline rocks becomes mobile at depths of 1.5-3.0 km and that at still deeper levels (5-10 km), "it is quite probably that melting of saline minerals takes place, accompanied by the formation of fluid jets rising upward just as jets of groundwater do. . ." [71, p. 163].

Certain manifestations of salt diapirism may be considered homologs of mud and sand volcanism; they can probably alter thicknesses of saline deposits just as strongly as mud volcanism can in terrigenous-clayey strata. Kosygin [2] has emphasized that compensatory or marginal synclines typically occur along with salt domes; saline strata in these synclines have decreased in thickness as a result of salt efflux to a dome.

Redistribution of plastic material also undoubtedly takes place in zones of intensive folding; however, quantitative assessment of this phenomenon is especially difficult. The difficulty consists in the fact that classification of folds, the mechanisms of their formation, and the deformation of the sedimentary and volcanogenic—sedimentary strata composing them are all closely interrelated. Moreover, the absence of a unified classification of folding does not allow us to make a precise quantitative estimate of this process, despite a series of remarkable reports by M. M. Teteyev, V. V. Belousov, E. Khaerman, V. A. Magnitskiy, A. Kosygin, P. N. Kropotkin, E. Khain, G. D. Azhgireya, A. E. Mikhaylov, V. V. Bronguleyev, A. V. Luk'yanov, and others.

In this connection, the assumptions of Seslavinskiy [53] that primary folding reduces the thickness of sedimentary strata by no less than 15% and that secondary folding causes 5-12% reductions are completely unsubstantiated. For some reason, it has been assumed that this reduction is primarily a result of compaction and reduction in porosity of the rock. At the same time, specialists in tectonics have demonstrated that intra-layer flow of material, the spreading and injecting of material in different parts of a fold system, plays a major role; this process is directly reflected in changes in thickness, but probably has a weak effect of the density of plastic rocks.

* * *

On the basis of the material presented, we can draw the following conclusions:

1. The Salop-Gilluly curve reflects a cardinal pattern in the sedimentary process. With development over time, thicknesses of sedimentary and volcanogenic—sedimentary deposits decrease as a result of increase in density, loss of a number of reactive components (H_2O , DOM, carbonates, unstable terrigenous minerals, etc.), and also redistribution of material in the lithosphere ("hydrovolcanism," "sand diapirism," formation of mud volcanos, salt tectonics, and folding). Minimal thicknesses of ancient deposits are most typical as a result.

2. The Salop-Gilluly curve is incorrectly referred to as a curve describing changes in sedimentation rate; it is correctly referred to as a curve describing rate of rock formation [56]. To infer changes in sedimentation rate over time, it is necessary to reconstruct initial thicknesses of sedimentary and volcanogenic—sedimentary strata which were present at the bottoms of paleo-water-bodies at the time of sediment burial.

3. In order to reconstruct initial burial thicknesses of sediments, it is necessary to use differential lithological-facial analysis rather than the general-geological methodology of coefficients (Seslavinskiy's age and duration factors [53]). In this type of analysis, after having determined the proportions as well as densities of the principal rock types in the section, it is necessary to calculate initial thicknesses corresponding to minimal densities of clays, sandstones, siltstones, or carbonate rock, based upon the curve shown in Fig. 3. Knowing the amount of residual DOM, as well as the amounts of sulfides and carbonates in rocks of the various lithological compositions, one can utilize a theoretically derived correction for losses of organic matter and carbonates [66, 69].

By carrying microscopic studies, analysis of mineral parageneses, and analysis of the most commonly encountered microstructures, one can take into consideration additional changes in thickness resulting from reorientation and dissolution of terrigenous grains under pressure.

Finally, by studying the patterns of diapirism, folding, and formation of stylolite joints, one can estimate their contribution to alterations in initial thicknesses of sedimentary strata in each individual case.

4. It is necessary to emphasize that the problem of changes in actual sedimentation rates over time still remains to be solved, because reliable reconstructions are lacking. From general considerations, it can be supposed that the sedimentation rate has increased overall from the Precambrian to the Quaternary to a degree which has accelerated all other geological processes; however, this supposition is very tentative.

LITERATURE CITED

1. A. M. Akramkhodzhaev, "Principal phase of oil formation," *Uzb. Geol. Zh.*, No. 6, 21-35 (1973).
2. N. N. Bakun, "Analysis of the epigenesis Mesozoic–Cenozoic deposits in rupture zones in local structures of the eastern regions of Central Asia," in: *Methodological Problems Associated with Lithology in Oil-and-Gas Regions* [in Russian], Nedra, Moscow (1979), pp. 93-160.
3. P. L. Bezrukov, "Breaks in deep-sea sedimentation and their geological significance," in: *International Geological Congress. 25th Session. Reports of Soviet Geologists* [in Russian], Nauka, Moscow (1976), pp. 149-156.
4. S. V. Bruyevich, "Rates of formation of bottom sediments in the ocean," *Tr. Inst. Okeanol.*, Akad. Nauk SSSR, 3, 90-118 (1949).
5. G. I. Gushinskiy, "Stylotites," *Izv. Akad. Nauk SSSR, Ser. Geol.*, No. 8, 30-57 (1961).
6. N. B. Vassoyevich, "An attempt to construct a type curve for gravitational compaction of clay rock," *Novyye Neftyanyye Tekhnol.*, Ser. Geol., No. 4, 56-72 (1960).
7. F. I. Vol'fson and N. A. Minskiy, "Deep level of formation of endogenous ore deposits in association with zoning of reservoir properties of rocks," *Izv. Akad. Nauk SSSR, Ser. Geol.*, No. 12, 87-100 (1972).
8. Yu. O. Gavrilov, *Diagenetic Transformations in Clay Deposits* [in Russian], Nauka, Moscow (1982).
9. G. S. Goldyrev and L. A. Kuznetsov, "An occurrence of stylolite structure," *Tr. Irkut. Un-ta*, No. 14, 211-230 (1959).
10. N. B. Dortman, V. I. Vasil'yeva, A. K. Veynberg, et al., *Physical Properties of Rocks and Mineral Resources of the USSR* [in Russian], Nedra, Moscow (1964).
11. M. A. Zharkov, *The History of Paleozoic Sedimentation* [in Russian], Nauka, Moscow (1978).
12. Yu. A. Zhemchuzhikov, *Principles of Coal Petrology* [in Russian], Akad. Nauk SSSR, Moscow (1960).
13. A. A. Ivanov and M. L. Voronova, *Halogene Formations* [in Russian], Nedra, Moscow (1972).
14. P. P. Ivanchuk, *The Role of Hydrovolcanism in the Formation of Gas-Condensate and Oil Deposits* [in Russian], Nedra, Moscow (1974).
15. M. Key, "Sediments and burial over time," in: *The Earth's Crust* [Russian translation], Izd-vo Inostr. Lit. (1957).
16. B. M. Keller, "General questions concerning the evolution of the Earth's crust during the upper Precambrian," in: *The Stratigraphy of the USSR. Upper Precambrian*, Gostekhizdat, Moscow (1963), pp. 120-158.
17. I. G. Kissin and S. I. Pakhomov, "Possible generation of carbon dioxide at depth at moderately high temperatures," *Dokl. Akad. Nauk SSSR*, 174, No. 2, 212-230 (1967).
18. I. G. Kissin and S. I. Pakhomov, "The geochemistry of carbon dioxide gas in abyssal zones of the subterranean hydrosphere," *Geokhimiya*, No. 4, 72-89 (1969).
19. A. V. Kopeliovich, "Microstylolites and some of their natural structural forms in sandstones of the Mogilevsk suite in the south-east of the Russian platform," *Dokl. Akad. Nauk SSSR*, 119, No. 2, 87-95 (1949).
20. A. V. Kopeliovich, "Amount of displaced material due to grain-size alteration as a result of secondary reconstitution of certain sedimentary rocks," *Byul. Mosk. Obshch. Ispytat. Prirody, Otd. Geol.*, 34, No. 2, 58-65 (1959).
21. A. V. Kopeliovich, *Epigenesis of Ancient Strata of the Southwestern Russian Platform* [in Russian], Nauka, Moscow (1965).
22. Yu. A. Kosygin, "Salt tectonics and gypsum tectonics of the Aktyubinsk region," *Izv. Akad. Nauk SSSR, Ser. Geol.*, No. 1, 30-42 (1940).

23. Yu. A. Kosygin, Principles of Tectonics of Petroliferous Regions [in Russian], Gostoptekhizdat, Moscow (1952).
24. F. P. Krendelev, "Rare occurrence of interesting stylolite joints," Dokl. Akad. Nauk SSSR, **154**, No. 3, 24-32 (1964).
25. A. Levorsen, The Geology of Oil and Gas [Russian translation], Mir, Moscow (1970).
26. A. P. Lisitsyn, "The rate of recent sedimentation in oceans," Okeanologiya, **11**, No. 6, 1957-968 (1971).
27. A. P. Lisitsyn, Sedimentation in the Ocean [in Russian], Nauka, Moscow (1974).
28. A. P. Lisitsyn, Avalanche Sedimentation and Breaks in Sedimentation in Seas and Oceans [in Russian], Nauka, Moscow (1988).
29. N. V. Logvinenko, Post-Diagenetic Alterations of Sedimentary Rock [in Russian], Nauka, Moscow (1968).
30. V. D. Lotmadze, "Stages in the formation of properties of clay rock and their lithification," Dokl. Akad. Nauk SSSR, **102**, No. 4, 23-25 (1955).
31. S. D. Malinin, "Physical-chemical characteristics of carbon-dioxides thermal springs," in: Geochemical Investigations in the Region of Elevated Pressures and Temperatures [in Russian], Nauka, Moscow (1965), pp. 92-107.
32. V. A. Maslov, "The formation of stylolite joints," Tr. Gorno-Geol. In-ta, No. 1, 27-32 (1958).
33. N. A. Minskiy, "Migration of regions of optimal reservoir properties," in: The Present State and Prospects for Investigation of Oil and Gas Reservoirs [in Russian], VNIGNI, Moscow (1971), pp. 27-45.
34. I. O. Murdmaa, "Oceanic pelagic lithogenesis," Litol. Polezn. Iskop., No. 5, 3-19 (1991).
35. Yu. V. Mukhin, The Compaction of Clay Sediments [in Russian], Nedra, Moscow (1965).
36. S. G. Neruchev, A. A. Trofimuk, and S. A. Ragozina, "Principal stages and quantitative aspects of generation and migration of hydrocarbons and source rocks," in: Generation of Hydrocarbons during the Lithogenesis of Sediments [in Russian], Nauka, Moscow (1976), pp. 120-158.
37. I. I. Nesterov, "Compaction of clay rocks," Sov. Geol., No. 12, 69-80 (1965).
38. L. G. Plakhotnyy, "Sutures and stylolites (based on an example of carbonate deposits on the Tarkhankutsk Peninsula)," Tr. UkrNIGRI, No. 3, 34-82 (1963).
39. B. K. Proshlyakov and T. I. Gal'yanova, "Stages of secondary alterations of quartz in sedimentary rock," Litol. Polezn. Iskop., No. 5, 32-48 (1971).
40. M. E. Raaben, "Rates of sedimentation during the Riphean," Izv. Akad. Nauk SSSR, Ser. Geol., No. 9, 117-130 (1966).
41. U. L. Russel, Principles of Petroleum Geology [in Russian], GONTI, Leningrad (1958).
42. H. Reading, Sedimentary Environments and Facies [Russian translation], Vol. 2, Mir, Moscow (1990).
43. A. B. Ronov, V. E. Khain, A. N. Balukhovskiy, and K. B. Seslavinskiy, "Changes in distribution, volume, and rate of accumulation of sedimentary and volcanogenic deposits during the Phanerozoic (within present-day continents)," Izv. Akad. Nauk SSSR, Ser. Geol., No. 12, 5-13 (1976).
44. L. B. Rukhin, Principles of General Paleogeography [in Russian], GONTI, Leningrad (1959).
45. V. N. Saks, "Rate of accumulation of recent marine sediments," Priroda, No. 6, 21-32 (1950).
46. L. I. Salop, "Geochronology of Precambrian and some features of the early stage of the geological Earth's evolution," International Geological Congress. 22nd Session. Reports of Soviet Geologists. Geology of the Precambrian [in Russian] (1964), pp. 40-86.
47. V. N. Sval'nov, Dynamics of Pelagic Lithology [in Russian], Nauka, Moscow (1991).
48. R. K. Selli, Introduction to Sedimentology [in Russian], Nedra, Moscow (1981).
49. M. A. Semihatov, Stratigraphy and Geochronology of the Proterozoic [in Russian], Nauka, Moscow (1981).
50. K. B. Seslavinskiy, "The influence of duration of stratigraphic intervals on estimates of sedimentation rates," Dokl. Akad. Nauk SSSR, **260**, No. 3, 701-706 (1981).
51. K. B. Seslavinskiy, "The age factor and estimation of sedimentation rate during the geological past," Dokl. Akad. Nauk SSSR, **260**, No. 4, 977-980 (1981).
52. K. B. Seslavinskiy, "The connection between sedimentation rates and compositions of deposits," Dokl. Akad. Nauk SSSR, **260**, No. 4, 1216-1220 (1981).
53. K. B. Seslavinskiy, "Sedimentation rates during the geological past," Byul. Mosk. Obshch. Ispytat. Prirody, Otd. Geol., **58**, No. 4, 29-48 (1982).
54. B. A. Sokolov and V. N. Kholodov, "Fluid genesis and fluid dynamics of sedimentary basins — a new direction in research," Otechestvennaya Geol., No. 6, 32-45 (1993).

55. N. M. Strakhov, Theoretical Principles of Lithogenesis [in Russian], Vol. 1, Akad. Nauk SSSR, Moscow (1960).
56. P. P. Timofeyev and V. N. Kholodov, "The evolution of sedimentation basins during the Earth's history," *Izv. Akad. Nauk SSSR, Ser. Geol.*, No. 7, 10-34 (1984).
57. V. A. Uspenskiy, "The origin of stylolite formations in Cambrian limestones of the Arals region," *Geokhim. Sb.* (1949), No. 1, pp. 20-41.
58. Dzh. M. Ueller, "Compaction of sediments," in: *Problems of Oil Geology in the Investigations of Foreign Researchers* [in Russian], GONTI, Leningrad (1961), pp. 50-97.
59. U. Feif, N. Price, and A. Thompson, *Fluids in the Earth's Crust* [Russian translation], Mir, Moscow (1981).
60. V. A. Khanin, *Terrigenous Rocks: Oil and Gas Reservoirs at Great Depths* [in Russian], Nedra, Moscow (1979).
61. N. I. Khimarov and S. D. Malinin, "Equilibrium phase relations in the system H_2O-CO_2 ," *Geokhimiya*, No. 7, 52-72 (1958).
62. V. N. Kholodov, "The problem of the origin of suture-stylolite joints," *Izv. Akad. Nauk SSSR, Ser. Geol.*, No. 2, 32-47 (1955).
63. V. N. Kholodov, "Sandy diapirism: a new aspect of catagenetic processes. Part 1," *Litol. Polezn. Iskop.*, No. 4, 3-32 (1978).
64. V. N. Kholodov, "Sandy diapirism: a new aspect of catagenetic processes. Part 2," *Litol. Polezn. Iskop.*, No. 5, 52-63 (1978).
65. V. N. Kholodov, "News concerning catagenesis. Part 2," *Litol. Polezn. Iskop.*, No. 5, 15-33 (1982).
66. V. N. Kholodov, *Post-Sedimentary Transformations in Elisional Basins* [in Russian], Nauka, Moscow (1983).
67. V. N. Kholodov, "The formation of gas-water solutions in sandy-clayey strata of elisional basins," in: *Sedimentary Basins and Their Oil and Gas Content* [in Russian], Nauka, Moscow (1983), pp. 28-45.
68. V. N. Kholodov, "The evolution of the sedimentary process during the Earth's history," in: *Problems of the Pre-Antropogenic Evolution of the Biosphere* [in Russian], Nauka, Moscow (1992), pp. 3-48.
69. V. N. Kholodov and R. I. Nedumov, *Lithology and Geochemistry of the Middle Miocene in Eastern Cis-Caucasia* [in Russian], Nauka, Moscow (1983).
70. V. N. Kholodov and R. I. Nedumov, "Sapropylitogenic organic matter as a factor affecting concentration of metals," in: *Accumulation and Conversion of Organic Matter in Recent and Mineral Sediments* [in Russian], Nauka, Moscow (1990), pp. 20-43.
71. A. E. Khot'kov and G. Yu. Balukonis, *The Formation and Geological Role of Groundwater* [in Russian], Nauka, Moscow (1968).
72. Ya. M. Chernousov, *Course in General Geology of Coal Deposits* [in Russian], GONTI, Moscow (1965).
73. M. V. Chivinskaya, G. D. Zabello, L. V. Smekalkina, and N. T. Turchanenko, "Types of salt diapirs and their role in the formation of local DDB structures," in: *Materials from the Symposium "Conditions of Formation and Oil and Gas Content of Salt-Dome Structures"* [in Russian], Naukova Dumka, Kiev (1966), pp. 24-36.
74. N. S. Shapskiy, "Structure and time," in *Novyy Knigi za Rubezhom*, No. 8, 24-36 (1951).
75. N. T. Shwartz and K. T. Laupper, "From carbonization of hay to formation of coal in nature," *Priroda*, No. 5, 24-36 (1930).
76. V. Engelhardt, "New aqueous solutions and catagenesis of rock," in: *Diagenesis and Catagenesis of Sedimentary Formations* [Russian translation], Mir, Moscow (1971), pp. 443-459.
77. A. A. Yakubov, A. A. Alizade, and M. M. Zeynalov, *Mud Volcanoes of Azerbaydzhan SSR* [in Russian], Akad. Nauk AzSSR, Baku (1971).
78. D. Blake and Ch. Roy, "Unusual stylolites," *Am. J. Sci.*, **247**, No. 11, 82-96 (1949).
79. P. Bodou, "L'importans distributive provinces joints stylolithique dans la compaction des carbonates," *Bull. Cent. Rech. Paris*, **10**, No. 2, 627-644 (1976).
80. B. N. Burma and Ch. M. Riley, "An unusual occurrence of microstylolites," *J. Sediment. Petrol.*, **25**, No. 1, 60-78 (1955).
81. T. A. Davies, W. W. Hag, J. K. Southam, and T. R. Worsley, "Estimate of Cenozoic oceanic sedimentation rates," *Science*, **197**, 53-55 (1977).
82. H. V. Dunnington, "Stylolite development post-date rock induration," *J. Sediment. Petrol.*, **24**, No. 1, 27-49 (1954).

83. J. Gilluly, "Distribution of mountain building in geological time," *Bull. Geol. Soc. Am.*, **60**, No. 4, 561-589 (1949).
84. M. T. Heald, "Stylolites in sandstones," *J. Geol.*, **63**, No. 2, 101-114 (1955).
85. H. D. Hedberg, "Gravitational compaction of clay and shales," *Am. J. Sci.*, **31**, 241-287 (1936).
86. A. Holmes, "The constructions of a geological time scale," *Trans. Geol. Soc. Glasgow*, **21**, 112-152 (1947).
87. Ph. H. Kuenen, "Rate and mass of deep-sea sedimentation," *Am. J. Sci.*, **244**, No. 8, 563-572.
88. C. S. Piggot and W. D. Urry, "Time relations in ocean sediments," *Bull. Geol. Soc. Am.*, **53**, No. 8, 1187 (1942).
89. H. H. Ricke and G. W. Chilingarian, "Compaction of argillaceous sediments: Development in Sedimentology," Vol. 16, Elsevier, Amsterdam (1974).
90. J. K. Rigby, "Some transverse stylolites," *J. Sediment. Petrol.*, **23**, No. 4, 265-271 (1953).
91. R. Revelle and F. P. Shepard, "Sediments of the California coast," in: *Recent Marine Sediments. A Symposium*, London (1949).
92. W. Shott, "Rate of sedimentation of recent deep sea sediments," in: *Recent Marine Sediments. A Symposium*, London (1939), pp. 409-415.
93. L. L. Sloss and D. E. Feray, "Microstylolites in sandstones," *J. Sediment. Petrol.*, **18**, No. 4, 212-218 (1948).
94. P. B. Stockdale, "Stylolites, their nature and origin," *Indiana Univ. Studies* 2, No. 35 (1922).
95. P. B. Stockdale, "Stylolites primary or secondary?" *J. Sediment. Petrol.*, **25**, 320-355 (1943).
96. P. B. Stockdale, "Stylolites with films of coal," *J. Sediment. Petrol.*, **16**, 212-240 (1946).
97. J. H. F. Umbgrove, "The pulse of the Earth," *Mart. Nijh.*, The Hauge, **358**, 230-242 (1947).
98. T. R. Worsley and T. A. Davies, "Sea level fluctuations and deep-sea sedimentation," *Science*, **203**, 455-456 (1979).

POST-SEDIMENTARY VARIATIONS OF DEVONIAN DEPOSITS OF THE CENTRAL TIMAN MOUNTAIN RANGE

I. M. Simanovich and V. V. Kostyleva

UDC 552.14:551.734(470.5)

The lithogenesis of terrigene and volcano-terrigenic Devonian deposits formed within the Timan rift-forming structure is considered. It is shown that the post-sedimentary transformations of volcano-sedimentary Devonian rock masses in the central Timan Mountain range are highly graduated and depend on the type of rock formation and on the facial membership of the deposits.

The lithogenesis of terrigene and volcano-terrigenic Devonian rock masses that were created within the Timan rifting region is characterized by a number of distinctive features. Thus, by comparison with rocks of the central Devonian field, which are comparable in terms of age and lithological composition, these rock masses are distinguished by a high degree of lithification. Investigations of Devonian rock masses that are variegated in terms of terrigene-volcanic features and were deposited under conditions of tectonic instability and intense volcanic activity have shown that their post-sedimentary transformations are highly graduated and depend on the rock associations and the sedimentation facies.

STRUCTURE OF GEOLOGICAL SECTION

The formations of terrigene and volcano-terrigenic rocks from the middle and upper Devonian period lies on a Riphean metamorphosed base, though is somewhat eroded (Fig. 1). Middle Devonian deposits are represented principally by alluvial and alluvial-deltaic monomict quartzite sandstone. Upper Devonian deposits (base of Lower Frasnian) occur discontinuously on top of rocks from the Middle Devonian or on rocks from the Upper Proterozoic. At the lower parts of the geological section, the Upper Devonian deposits partially retain the habit inherited from the Middle Devonian and remain mainly quartzite in composition. Higher up in the section there occurs a pronounced admixture of feldspar, lithoclasts of siltstone, and rocks from the Riphean base in the quartzite deposits. This is obviously connected to the powerful tectonic reconstruction of the structural plan in regions framing the central Timan Mountain range that had caused the new sources of ablation to appear.

Higher up in the section the sandy alluvial-deltaic and coastal deposits are gradually supplanted by a cyclically structured sandy-silt-clay marine rock mass that has long been known in the region of the central Timan Mountain range as the Paschija-Kyn strata. In the upper parts of the rock mass an admixture of dissociated hyaloclastic is present, which may possibly attest to synchronous volcanism. Higher up in the section within the same cyclic marine rock mass, there occur local tuff formations, which are sometimes thick (up to 200 m), as well as basalts of the Valsa sheet, which occupy an area of more than 1600 km².

The majority of researchers claim the volcanic complex to be a unified formation, contrasting it to the terrigene complex of the Paschija-Kyn structural substage. V. G. Getsen [2] distinguished among the deposits of the Frasnian stage a terrigene and trappian formation, considering the latter, moreover, as a tuff and basalt rock mass. Consequently, it was assumed that the tuffs constitute an eruptive facies of basalt volcanism. Moreover, in the course of geological prospecting activity (1964), it was established that there exists a terrigene marine rock mass about 22 m thick between the thick mass of tuffs and basalts of the Valsa sheet. Thus, tuff eruptions and discharges of plateau-basalts are substantially separated in time.

According to our information [6], the interrelations between magmatism and sedimentation in the Frasnian are highly complicated. Basalt melts in interjacent chambers that interact phreatically with included flooded sedimentary strata resulted in the formation of pyroclastic flows that erupted on the floor of the sea basin. The latter formed masses of

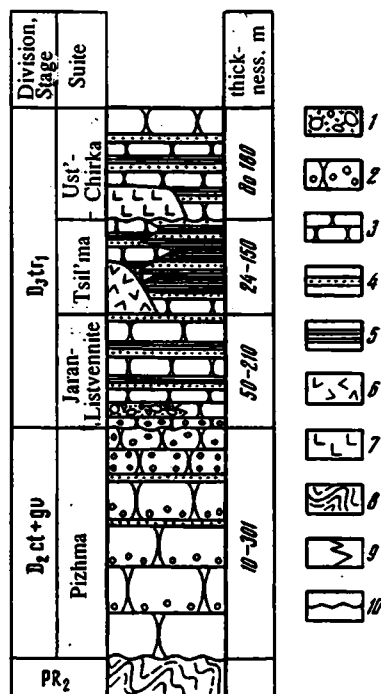


Fig. 1. Composite geological section of Devonian deposits of the northwest part of the central Timan Mountain range (including data gathered by A. E. Tsaplin). (1) conglomerates; (2) sandstone with inclusions of pebbles and gravel; (3) coarse- to fine-grained sandstone; (4) siltstone; (5) siltstone-mudstone; (6) xenotuffs; (7) blanket basalt; (8) clay shale; (9) facial boundaries; (10) erosion boundaries.

xenotuffs, which are a major component of Upper Devonian volcano-sedimentary sections of the Timan Mountain range. Build-up of cyclically structured marine sediments, though now contaminated with an abundance of rewashed hyaloclastic, continued following the formation of the tuff mass. Massive discharges of basalts occurred later than the tuff eruption, and on the surface of the post-tuff marine sediments, though most likely through the effect of the same deep-seated magmatic chamber.

Thus, there are geological events in the history of the Devonian deposits in the central Timan Mountain range that have been imprinted in the rock composition and structure of the geological section. We are thus able to designate natural event-based datum lines that can serve as a basis for partitioning these deposits into natural lithological complexes. In the Middle Devonian (on the basis of the palynological data, the Eifelian and Givetian stages) we have identified a sandy quartz Pizhma suite corresponding to the block of the Pizhma rock mass identified by A. E. Tsaplin [8]. Because of the occurrence of unweathered material in weathered rock at the interface between the Middle and Upper Devonian, we are led to segregate in our description of the lower part of the Jaran-Listvennite suite the rocks that essentially lack any indicators that would attest to synchronic volcanism. Massive eruptions of xenotuffs and the occurrence of rewashed hyaloclastic in the composition of rocks that originated in the sea corresponds, we believe, to the bottom of the Tsil'ma suite. Because of local build-up of the volcanic rock masses and irregularities in the topography of the sea flow, the deposits in this suite possess a highly variegated facial composition. The entire stage, from the start of the build-up of the sandstone of the Jaran-Listvennite suite to termination of the build-up of the multi-facies rock mass of the Tsil'ma suite may be considered a unified transgressive macrocycle complicated by eruptive volcanism.

Shallow-water sand-silt marine deposits with eroded boundaries which we, following Tsaplan [9], are referring to as the Ust'-Chirka suite, overlie the sand-silt-clay mass of the Tsil'ma suite. The deposits of this suite signify the start of a new transgressive sedimentary cycle that continued (in the Sargaevo era) with the build-up of a clay-carbonate rock masses.

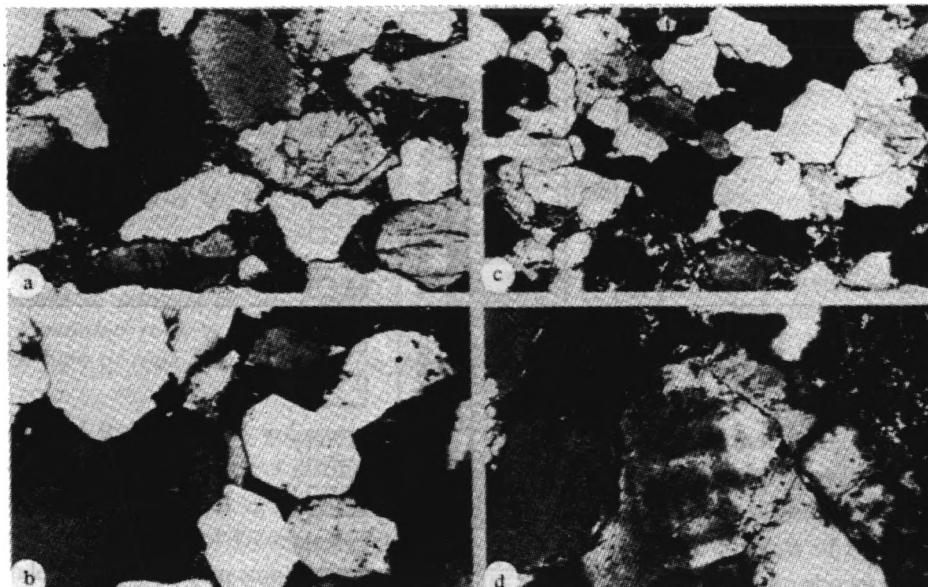


Fig. 2. Post-sedimentary variations of sandstone. (a) microstylolites in quartzzy sandstone of the Pizhma suite (magnification 30 $\times$); (b) regeneration of quartz grains with regular crystallographic faceting in quartzzy sandstone of the Pizhma suite (magnification 30 $\times$); (c) quartz regeneration with latticed silicification in sandstone from the Pizhma suite (magnification 30 $\times$); (d) regeneration of fragmental grains of orthoclase (magnification 60 $\times$).

Each of the four suites we are considering (the Pizhma, Jaran-Listvennite, Tsil'ma, and Ust'-Chirka) are characterized by specific contrasting manifestations of post-sedimentary transformations.

POST-SEDIMENTARY TRANSFORMATIONS

Pizhma Suite. The greater proportion of the Pizhma suite is represented by quartzzy sandstone, predominantly medium-grained, with different degrees of grading. The roundness of the fragmental material varies, though semirounded grains predominate. Average to extensive erosion of the clay material, the presence or absence of which causes different kinds of post-sedimentary variations occurs naturally in the deposits. The rock mass as a whole is polycyclic, moreover with poorly graded coarse-grained sandstone, sometimes gritstone and fine-grained pebbled conglomerate, found at the base of the cyclites and crowned (in the complete cyclites) by horizontally chatoyant laminar siltstone. The thickness of the sandstone of the Pizhma suite varies over a broad range. Thus, on the basis of the profile constructed from data gathered from drilling across the dominant strike of the rock, the thickness of the section increases in abrupt stages from 60 to 300 m over a short distance (20 km) [4]. On the whole, the rock mass is related to deposits of an ancient riverine system that accumulated in a tectonically unstable setting created by the formation of a rifting structure [4].

As a rule, highly eroded quartzzy sandstone and quartzzy sandstone with filmy hydromica cement alternate in the sections. In the latter diffusion structures have developed under the effect of pressure, and these are often conformal structures, though sometimes microstylolites are readily observed (Fig. 2a). There is virtually no regeneration of quartz in these intercalations. There are no diffusion structures in the highly eroded sandstone structures, though nevertheless quartz regeneration has developed. Authigenous quartz only partially fills the interstitial spaces (porosity 5-10 vol. %). Often, markedly faceted regenerated margins are observed (cf. Fig. 2b). Sandstone containing regenerated quartz in highly eroded intercalations correspond roughly to the proposed quantity of silicic acid that had entered into solution in the intercalations with hydromica cement as a result of the development of diffusion structures under the effect of pressure. Obviously, SiO_2 solutions in some of the layers is attributable to the redeposition of SiO_2 in the other layers. Sometimes, alternating microlaminas exhibiting highly developed diffusion structures and with quartz regeneration but without diffusion structures may be observed within the confines of a section. This undoubtedly attests to a local increase in the pH in intercalations that have become enriched with hydromica and redeposition of mobilized silicic acid in adjacent layers under neutral

conditions. The rate of the process, which began on some stage of the post-sedimentary transformations, may be assumed to be high; if the quartz diffusion process were to have occurred slowly, compensation of the alkali-acid conditions as a result of diffusion could be assumed to have occurred, and the ultimate result would have unavoidably been different.

Despite how paradoxical it may appear, the type of structure formation exhibited by the quartzite sandstone that we have described is characteristic of the relatively narrow-width and least buried sections of the Pizhma suite. The most deeply buried sandstones, which were discovered in borehole 5145, are, on the whole, more highly lithified (hard), and are characterized by weakly developed diffusion structures created under the effect of pressure in intercalations containing hydromica cement and intensive quartz regeneration in the highly eroded layers, moreover the porosity of layers with an abundance of authigenous quartz is low. The quantity of silicic acid, which, we believe, is supposed, is mobilized as a result of the development of diffusion structures and redeposition in the highly eroded layers is clearly insufficient to produce this formation. It is reasonable to assume that there had existed a supply of silicic acid from certain external sources. This is confirmed by the presence in the sandstone of borehole 5145 of latticed silicification, moreover rocks with composition containing hydromica cement are also silicified. In the silicified segments a confluent structure entirely lacking any porosity is observed (cf. Fig. 2c); here the authigenous quartz has also absorbed the clay component. The presence of latticed and streaky silicification undoubtedly attests to the introduction of SiO_2 , possibly as a result of hydrothermal activity. Such silicification is undoubtedly an early process, since, despite the presence of hydromica cement, diffusion structures are entirely absent from the unsilicified segments; obviously, the latticed quartz framework obstructed the transmission of pressure to quartz grains in the rock mass. Intensive quartz regeneration is also apparently unrelated to the diffusion structures, and is sometimes confined to the upper parts of the section of the Pizhma suite. It is possible that the abundance of silicic acid would have been caused in this case by evolution of rock to the surface, erosion of the rock, and penetration of vadose water.

Segregations of chalcedony are sometimes found in interstitial spaces in the upper parts of sections of the Pizhma suite that had formed between regenerated margins of quartz grains. Consequently, chalcedony is a relatively late, post-sedimentary mineral. It would appear that the creation of chalcedony was due to the penetration of vadose water relatively highly saturated with silicic acid.

Hydromica with insignificant quantities of swelling interlayers is the principal clay mineral in sandstone from the Pizhma suite. Hydromica is entirely unweathered in rocks with latticed silicification in which, obviously, post-sedimentary processes had already ceased. The unweathered or slightly weathered hydromica most likely constitutes a sericitic detritus from eroded Riphean mica schist. The chlorite which is sometimes present in small quantities is also apparently of terrigenous origin.

In samples of Pizhma sandstone taken from borehole 433 intensive kaolinitization of hydromica is observed both in the interstitial spaces as well as in the interbeds between grains possessing conformal and microstylolite contacts. Consequently, kaolinitization developed later than diffusion of quartz grains under the effect of pressure. In samples from borehole 433 barite veins which, perhaps, may be related to hydrothermal processes caused by activation of volcanic activity are also observed; the section taken from borehole 433 is crowned with a tuff formation. It may be assumed that kaolinitization was also caused by these processes.

Jaran-Listvennite Suite. The section of the suite that is characterized by cyclic alternation of sandstone, siltstone, and claystone with textures that are typical for shallow-water deposits is represented most completely in several of the boreholes (5145, 6-K, 7-K). As we have already noted, the base of the suite (Jaran layers) is represented primarily by sand and gravel-sand deposits with alluvial or deltaic habit. There is a gradual tapering of the granulometric composition of the rock as we move upwards in the geological section. On the whole, prior to the start of intensive volcanic activity the region of the Tsil'ma Cliff was part of a shelf sea, where mainly clayey-siltstone and fine-sandy sediments had settled. To the east and northeast of the region, a narrow facies zone of sandy and coarse-sandy deposits, the accumulation of which was caused by the existence of an intrashelf barrier, may be traced from data derived from the boreholes and outcroppings.

Besides the dominant quartz, insignificant admixtures of orthoclase and albite (1-3%) and lithoclase (5-30%), represented mainly by mica schist (apparently, from the basement) and clayey-silt rocks, which are erosion products from the Devonian deposits, are found in the sandstone and siltstone. Weathered and semi-weathered biotite (up to 1%) is found. In the upper parts of the section green chloritized fragments, possibly of volcanic origin, occur. The degree of erosion varies in sandstone taken from the base of the suite; the content of clay minerals oscillates from 1 to 10%.

Resorbed structures that regenerated conformally under the effect of pressure, sometimes microstylolites, occur in the sandstone. However, the level of development of these structures does not depend that explicitly (by comparison with the Pizhma rocks) on the content of clay minerals. This may be attributed to the fact that even in highly eroded sandstone there are significant quantities of lithoclasts with mica and hydromica that lead to the appearance of an alkaline medium once pressure-induced diffusion structures develop. Here there is also no selectivity of the degree of quartz regeneration as a function of the extent of erosion of the rock in the Pizhma sandstone. The most intensively developed quartz regeneration is observed in the arenaceous rock of the Jaran-Listvennite suite exposed in boreholes 5242 and 5241 in the northern part of the region and in boreholes 5145, 7-K, and others in the near-axial part of the rift structure. The quantity of deposited silicic acid clearly exceeds the quantity of silicic acid that could be mobilized in pressure-induced desorption of quartz grains, which leads us to suggest an additional source of SiO_2 .

In the sandstone from a number of boreholes, regeneration of orthoclase (cf. Fig. 2d) is observed, moreover throughout the district the process is clearly confined to the south-southwest part of the region under study (boreholes 5121 and 5140). The intensity of the regeneration falls gradually towards the east. Regeneration of orthoclase at the base of the section of the Jaran-Listvennite suite (where it is generally apparent) is encountered most often. There is no apparent relation between regeneration and diffusion of feldspar under the effect of pressure; the regenerated margins of orthoclase are xenomorphic relative to the authigenous quartz and sometimes entirely envelop it. This leads us to conclude that the origin of the authigenous orthoclase is relatively early, and that the laws governing its localization lead us to suggest either specific conditions of salinity in the corresponding segments of the sedimentation basins or local hydrothermal seepage of solutions with elevated potassium concentration.

The clay minerals are represented by a mixture of hydromica and chlorite. Fragments of lithoclast from which mica and chlorite were liberated in fragmentation of the samples, causing them to turn into small fractions, constitute an additional source of these minerals in fractions measuring less than 0.001 mm. Chlorite and muskovite is also distributed in the biotite. Chloritization of a few rock fragments (in the upper parts of the suite) that have been hypothesized as hyaloclast is noted.

X-ray diffraction analysis demonstrated that fractions measuring less than 0.001 mm are represented by a mixture of hydromica and chlorite in varying proportions. Chlorite is characterized by a high peak strength $d_{(002)} = 7.1 \text{ \AA}$ with insignificant $d_{(001)} = 14.3 \text{ \AA}$. This relation of peak strengths is typical of ferrous chlorite. To verify the presence of kaolinite in the fraction treatment in a 10% HCl solution for 2 h was performed. The strength of the $7 \text{ \AA}$ peak dropped markedly, whereas the undissolved residue most likely actually corresponds to an insignificant admixture of kaolinite (Fig. 3A). Kaolinite is observed in very small quantities under the microscope. It partially replaces hydromica and is distributed in some of the fragments.

Tsil'ma Suite. The petrographic composition of rock from the Tsil'ma suite is highly heterogeneous as a result of the start of volcanic (eruptive) activity and the variegated conditions of sedimentation. At the base of the suite there are numerous xenotuff bodies present, the thickness of these bodies reaching 200 m; they occupy an area of several dozen square kilometers. The marine rock masses that are synchronous with the latter as well as being of analogous facies composition are contaminated with hyaloclasts that are, to some extent, dislocated (rounded) and are of the principal composition, the content of which in the rocks increases upwards in the section. Irregularities in the topography of the floor of the shelf sea caused by the existence of the barrier (since the Listvennite era) to which numerous tuff structures edifices are confined, led to the formation of sea deposits possessing a variegated facies composition. Above the xenotuffs there are cyclically structured rock masses, mainly silt-sand rock masses with intercalations containing brecciated conglomerates. In regions at a distance from the tuff edifices, facies of silt-clay or fine sand deposits that, on the whole, crown the section of the Tsil'ma suite predominate.

We have described xenotuffs and their secondary variations in considerable detail in a previous article [6]. Xenotuffs of psephite dimensions consist mainly of highly variegated hyaloclast with extremely odd shapes containing impregnations of orthoclastized plagioclase, rounded liquated secretions, and amygdules containing kaolinite, calcite, and, rarely, zeolite. Visually invariant greenish isotropic hyaloclast, though resembling the crystallized varieties, are represented by magnesian ferrichlorite. Kalifeldspathization of plagioclase and, in part, chloritization of glass could have occurred with saturation of the melt in mica and an intermediate chamber or in the course of migration of pyroclastic fragments. There is, however, evidence for thorough transformation of glass even in the sediment. Thus, there is often present around the glass fragments a margin consisting of leucoxene. The high content of titanium within this margin, as well as potassium,

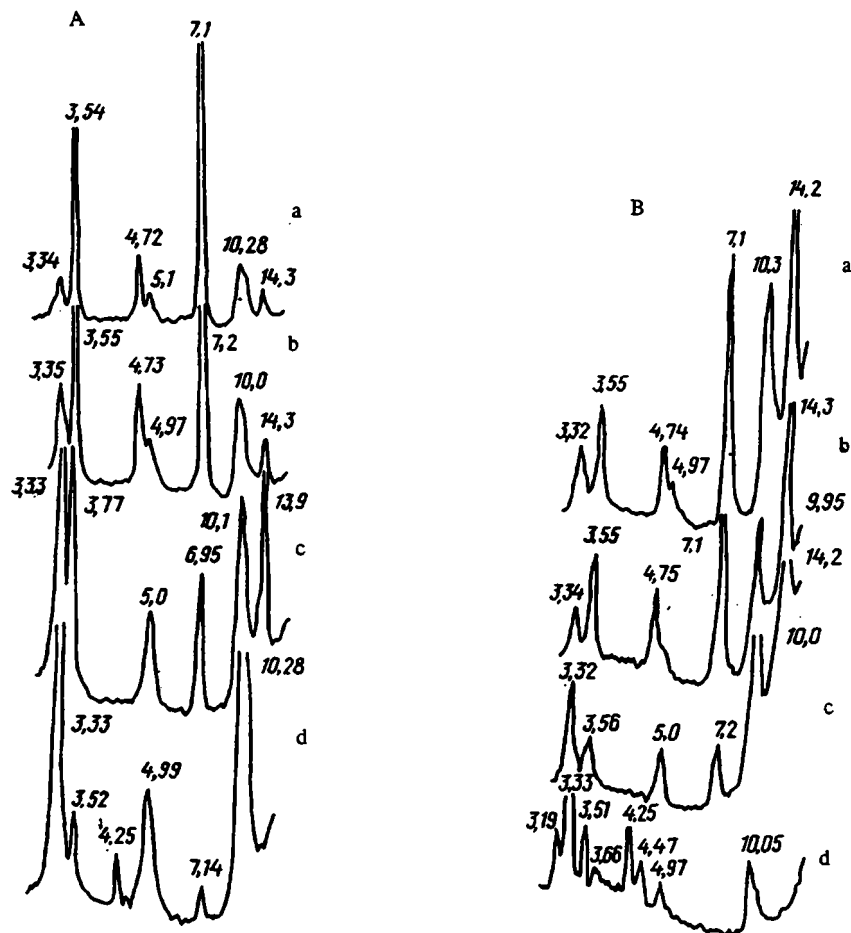


Fig. 3. Typical diffraction patterns of associations of clay minerals (fractions >0.001 mm) of the Jaran-Listvennite (A) and Tsil'ma (B) Upper Devonian suites. (a) native sample; (b) glycerin-saturated sample; (c) sample calcined for 1 h at 550°C ; (d) sample treated for 2 h by boiling in a 10% HCl solution.

are confirmed by the data of micro-probe chemical analysis, moreover in the fragments themselves the content of these elements is low. This attests to evacuation of titanium and alkalis, which may be confirmed only under acidic conditions; the acidity of the medium is underscored by the formation of kaolinite in certain amygdulites and hyaloclasts. It may be assumed that large quantities of acidic gases of juvenile origin were evacuated from the highly fluidized fragments of solidified glass.

The percentage of redeposited (and rounded to some extent) hyaloclastites in the tuffites and tuffaceous sandstone and siltstone is in the range 10-60%. Isolated intercalations of almost pure quartz sandstone are also present in the rhythmically structured sandy-silt sections of the Tsil'ma suite. Ordinary conformably regenerated structures at high (up to 10%) porosity are also found in these sections. Once the content of the hyaloclast reaches 15% and more, marked intensification of regeneration of fragmental quartz may be noted. This phenomenon, in particular, is observed in the tuffites that immediately overlie the xenotuffs and contain as constituents both dislocated (rounded) and nondislocated fragments of transformed glass. Here diffusion structures are lacking, which points to early (diagenetic) regeneration of the quartz. Obviously, in diagenesis desilification of glass with substitution of Mg-Fe-chlorite for the glass continued. Deposition of silicic acid might have contributed to the weakly acidic medium arising as a result of acidic gases occluded in the glass. This hypothesis is confirmed by the frequent presence of kaolinite of clearly secondary genesis which is distributed in all the glass fragments and in the interstitial spaces. The formation of kaolinite was also an early process, inasmuch as kaolinite is sometimes entrapped by authigenous quartz.

Intensive carbonatization of tuffites and tuffaceous sandstone and siltstone is observed far less frequently, moreover nearly all the fragmented grains are corroded and substituted here, while there is no authigenous quartz present. This would appear to attest to significant variations in the acidity-alkalinity ratio during accumulation of post-tuff sediment.

In isolated instances regeneration of fragmented orthoclase grains that are often encountered in rocks of the dimensions of sand is observed.

A clayey fraction (measuring less than 0.001 mm) in the tuffs and tuffites is often represented by a mixture of hydromica containing small quantities of swelling layers and magnesian ferrichlorite, which is completely dissolved upon treatment in hydrochloric acid (cf. Fig. 3B). Recall that in rocks from the Jaran-Listvennite suite chlorite is represented by a ferric variety. The high magnesium content of the chlorites present in the tuffaceous rocks of the Tsil'ma suite is obviously caused by the predominance of hyaloclasts of the basic composition.

Ust'-Chirka suite. We have already remarked that sand-silt rocks occur with eroded products on top of the sand-clay formations of the upper parts of the Tsil'ma suite and signify the presence of a new macrocycle of sedimentation. Sedimentation apparently occurred in a tectonically nonquiescent setting and different types of catastrophic phenomena may be observed together with the normal sedimentation of a shallow-water shelf. Thus, in the lower parts of the section brecciated conglomerates with an abundance of large plant detritus, sometimes carbonized with horsetern and fern trunks, is observed in places. The appearance of such coarse subaqueous slumped deposits would appear to have been controlled by acute variations of the base level of erosion. Intercalations (measuring up to 1 m) of xenotuffs with nondislocated, coarse (up to 5-20 mm) hyaloclasts are found among tuffaceous sandstone and siltstone containing eroded hyaloclast, attesting to sporadic eruptive volcanic activity. Ostracod thanatocoenoses (in intercalations measuring 5-10 cm thick, saturated with fine vesicles) are found on roughly the same levels. Numerous magmatic bodies with basaltic compositions, apparently of sill, have been discovered by means of boreholes that have been drilled to the north of the latitudinal segment of the Tsil'ma River. Thus, sedimentation in the Ust'-Chirka eon occurred during a period when tectonic and volcanic rift-forming activity was dormant. Sandstone and siltstone usually containing from 20 to 60% eroded hyaloclast resemble, in terms of type of transformation, the types of rocks from the Tsil'ma suite described earlier. Varieties in which regenerated fragmental quartz is densely distributed in the sandstone and siltstone are observed, and kaolinite is also present. As we have already noted, deposition of authigenous quartz was caused by desilification of glass fragments under acidic conditions. Sandstone and siltstone that are highly carbonized are interbedded with these varieties, together with poikilitic calcite cement. And, finally, tuffaceous sandstone with green basal chloritic cement is sometimes found. In these intercalations and lens of brecciated conglomerates, which contain numerous pellets of siltstone and aleuropelites (with dimensions varying from 0.5 to 15 cm), carbonatization is usually accompanied by the formation of abundant segregations of rhomboidal siderite (0.01-0.1 mm). Ordinary conformally regenerated structures are distributed in rarely encountered intercalations of, mainly, quartz. Along a wide portion of the Tsil'ma River occurrences of copper-silver ore in rocks from the Ust'-Chirka suite have long been known, and these ores have been exploited since the sixteenth century, moreover the first Russian silver coins were stamped out from the smelted silver. The ore deposits are confined to subaqueous slumped sandstone and brecciated conglomerates with numerous and sometimes very large (measuring up to several meters) carbonized plant residues. Copper minerals are distributed only in the plant residues, replacing it, as well as along cleavage cracks, and are represented basically by chalcocite, and, in small quantities, copper mica and native copper. Pirite and native silver, the latter in the form of very fine inclusions in the chalcocite, sometimes in the form of circuits running along the cleavage cracks, are occasionally found. The content of copper in the plant residues reaches 18%.

The special historical significance is responsible for the increased interest in the genesis of the Tsil'ma manifestations of copper-silver ores. Usually, copper mineralization on the Tsil'ma River is generally related to endogeneous processes, such as volcanism and hydrothermal activity. While this would appear to be the case, we would like to advance a hypothesis that makes specific the possible processes that could have led to the formation of copper-silver minerals.

On the one hand, there can be no doubt that there exists clearcut control over ore mineralization, since the concentrations of carbonized plant residue are confined to shallow-water marine subaqueous slumped brecciated conglomerates. From this circumstance it follows that deposition of copper and silver minerals occurred directly from the sea water. Under conditions where there is no hydrosulfuric contamination and, consequently, no low sulphide sulphur potential, decomposed wood parenchyma served as a geochemical barrier on which deposition of copper and silver occurred.

The elevated concentrations of Cu and Ag in waters from the Ust'-Chirka marine basin are probably due to rifting and associated volcanism. Let us consider what are the possible mechanisms for introduction of Cu and Ag into sea water.

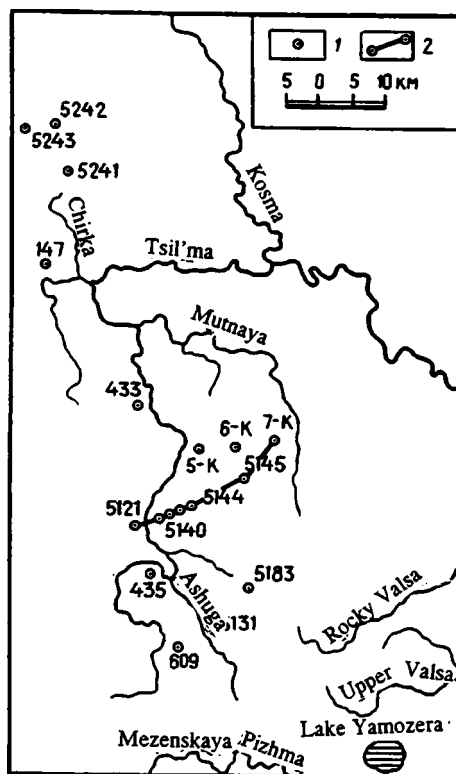


Fig. 4. Relative locations of geological sections of the transverse profile that are discussed in article: (1) bore-holes; (2) profile lines.

1. Decay of Hyaloclastic. The process is highly unlikely, since eruptive volcanism in the Tsil'ma eon developed far more intensively, while copper mineralization processes were absent.

2. Leaching of Cu and Ag from Basalt into Post-Eruptive Processes Occurring as the Flows into the Sea Water Varied. In our previous studies [7] it was demonstrated that this process is a realistic one under the conditions of the ocean floor, though in the present case we are considering a shallow-water basin with essentially different chemical conditions. Moreover, there is no proof that the numerous basalt bodies that alternate with the marine sediments of the Ust'-Chirka suite are related to subaqueous variations rather than the sills.

3. Leaching of Cu and Ag from Basalts as a Result of Circulation of Sea Water (Convective Cells). This phenomenon has been demonstrated in numerous studies that have considered rocks from the secondary layer of the oceanic crust [5]. This process is also highly unlikely, since in the sections of the Ust'-Chirka suite the sand-silt formations markedly dominate the basalt rock masses, hence under conditions in which the formations are highly permeable fracture, circulation in the basalt is scarcely possible.

4. Delivery of Cu and Ag Together with Other Elements Directly into Fluid Flow from Rift Faults. G. Yu. Butuzov [1] demonstrated that this process is the most likely one for the classical case illustrated in the build-up of metalliferous deposits of the Red Sea. Therefore, if we agree that post-Devonian volcanism in the central Timan Mountain range was riftogenic in nature, we are justified in assuming that endogenous fluidal evacuation of the elements we are concerned with occurred on the floor of the sea basin. Most likely, districts in which Cu and Ag concentrations in the sea water are high coincided with flows through subaqueous trenches of run-off that supplied the plant residue. The combination of these two factors is probably responsible for the formation of the ore deposits.

Thus, post-sedimentary transformation of terrigene-volcanic Devonian formations of the central Timan Mountain range is characterized by the following specific features:

1. Elevated degree of lithification by comparison with contemporary rocks of the main Devonian field.
2. Confinement of the transformations to early stages, diagenesis and, in part, initial epigenesis.

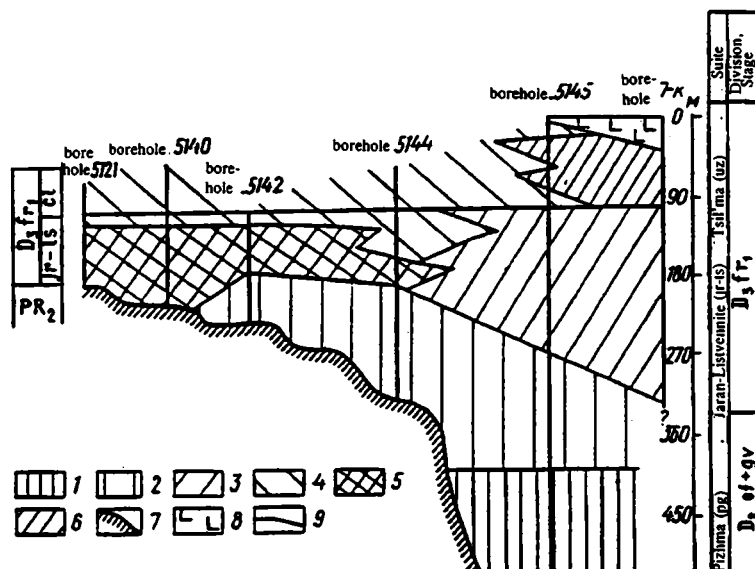


Fig. 5. Distribution of different zones of post-sedimentary transformation along the lateral and across the section (transverse profile). (1) zone of latticed and streaky silicification and intensive quartz regeneration (lower parts of section of Pizhma suite); (2) zone of alternation of layers with diffusion structures and with quartz regeneration (Pizhma suite); (3) zone of most intensive regeneration of fragmental quartz in sandstone from the Jaran suite; (4) zone of conformably regenerated structures in the Upper Devonian sandstone; (5) zones with regenerated orthoclase; (6) zone of quartz regeneration in tuffaceous sandstone and tuffite from the Tsil'ma suite; (7) surface of basement; (8) basalts of the Valsa shield (Ust'-Chirka suite (uz); (9) stratigraphic boundaries.

3. Direct or intermediate influence of volcanic processes on the degree of lithification and nature of the post-sedimentary processes.

It is known that the terrigenous rocks of the main Devonian field are virtually uncemented. For example, the Middle Devonian Starooskol horizon (developmental analog of the Pizhma suite) discovered in the Kuvshinov borehole (Tver' district) is represented by unconsolidated, primarily quartz sand, despite the fact that the thickness of the overlying rock mass (disregarding eroded segments) reaches 800 m.

Lithification of the sand-silt rock from Middle and Upper Devonian deposits of the central Timan Mountain range is due, basically, to the formation of regenerated quartz cement, more rarely carbonatization. As was demonstrated in the previous part of the present study, authigenous quartz is polygenetic. Latticed silicification and authigenous quartz at the base of the Pizhma suite (borehole 5145) most certainly formed as a result of introduction of silicic acid into the unconsolidated quartz sand. The authigenous quartz present in the upper parts of the Pizhma suite is of diagenetic origin, apparently as a consequence of the introduction of silicic acid by vadose water. Silicification of the tuffaceous sandstone and tuffites of the Tsil'ma and Ust'-Chirka suites are attributable, we believe, to desilification of hyaloclasts under the conditions imposed by an acidic medium in the diagenetic process of glass transformation.

It is more difficult to explain the formation of authigenous quartz as a result of the development of diffusion structures under the effect of pressure in adjacent intercalations, which is typical of sandstone from the Pizhma suite. In general, the combination of diffusion structures with quartz regeneration is considered the most typical sign of deep-seated epigenesis [3]. However, these structures are found in the shallowest parts of the section of the Pizhma suite. Despite the fact that the Timan Mountain range is very highly eroded, there are no data indicating that the thickness of the overlying rock mass reaches, for example, 1000 m, or somewhat exceeds this figure for sand from the Main Devonian field. A markedly contrasting separation, namely the diffusion structures in intercalations with hydromica cement and authigenous quartz in highly eroded rocks, attests to a high rate of diffusion, or introduction, or deposition of silicic acid, which precedes diffusion adjustment of the acidity - alkalinity relation. It may be supposed that until some definite point the quartz sands were unconsolidated though overlain with sea rocks from the Jaran-Listvennite suite. Apparently, the onset of volcanic processes and the associated increase in heat flow in the rift zone also served as a triggering mechanism that

activated the geologically instantaneous development of diffusion structures under the effect of pressure and the dependent process of quartz regeneration. Consequently, this process likewise could hardly be considered a deep-seated epigenetic process.

The degree of lithification of rock and type of transformations depend, on the whole, on the depth of occurrence of the rock and its proximity to the axial part of the fault trough structure (Figs. 4 and 5). No well-defined relation between the variations in the rocks and fissures and the intensity of folding is observed.

The development of copper-silver mineralization is obviously an example of the direct influence of volcanism on post-sedimentary processes.

REFERENCES

1. G. Yu. Butuzova, "Looking once again at the question of determining the sources of metal in hydrothermal oceanic ore formation," *Litol. Polezn. Iskop.*, No. 1, 114-119 (1989).
2. V. G. Getsen, *The Tectonics of the Timan Mountain range* [in Russian], Nauka, Leningrad (1987).
3. A. V. Kopeliovich, *Epigenesis of Ancient Formations of the Southwest Portion of the Russian Platform* [in Russian], *Proc. Institute of Geology, USSR Academy of Sciences*, No. 121 (1965).
4. V. A. Kostyleva and I. M. Simanovich, "On the genesis of the Pizhma sandstone of the central Timan Mountain range," *Litol. Polezn. Iskop.*, No. 3, 56-64 (1990).
5. V. B. Kurnosov, *Hydrothermal Variations of Basalts in the Pacific Ocean and Metallogenic Deposits* [in Russian], Nauka, Moscow (1986).
6. I. M. Simanovich and V. V. Kostyleva, "Xenotuffs and Lower Frasnian deposits of the central Timan Mountain range," *Litol. Polezn. Iskop.*, No. 3, 56-64 (1990).
7. I. M. Simanovich and S. G. Skolotnev, "Initial variations of basalts and their possible contribution to sedimentation," *Litol. Polezn. Iskop.*, No. 6, 54-68 (1988).
8. A. E. Tsaplin, "Basic features of the structure of Middle Devonian deposits in the northwestern portion of the central Timan Mountain range," *Izv. Vuzov, Geol. Razvedka*, No. 12, 48-56 (1982).
9. A. E. Tsaplin, "Basic features of the structures of the Jaran and Listvennite suites of the Lower Frasnian in the northwestern portions of the central Timan Mountain range," *Izv. Vuzov, Geol. Razvedka*, No. 6, 15-20 (1984).

THERMODYNAMIC MODELING OF HYDROCHEMICAL PROCESSES IN THE PERSALT SERIES IN THE AREA OF THE UPPER KAMA RIVER

V. P. Zverev and L. V. Migunov

UDC 550.4:552.53(470.5)

An integrated thermodynamic and mineralogical evaluation of the hydrogeochemical processes that arise in the interaction of subsurface water with hydrogenous minerals (calcite, dolomite, gypsum, halite) in a persalt rock mass from the area around the Upper Kama River is given. Good agreement between the mineralogical zonation of calcite, gypsum, and halite in fissures in the carbonate-clay rock mass and the degree of saturation of the subsurface water with these minerals is shown.

Knowledge of the direction of hydrogeochemical processes in a persalt rock mass from the Upper Kama region is not only of theoretical importance, but also of practical interest in view of the demands for integrated study of water-protective formations in deposits of potash salts. It is impossible to arrive at an evaluation of the safety of existing and projected potash mines without first studying the contemporary and prospective direction of processes that occur in the interaction between solid and liquid phases, and without first determining the most probable products of this transformation. Computer simulation based on methods of equilibrium thermodynamics [2, 3] is usually employed here. Such an approach to the physical and chemical development of natural systems is based on the principle of partial equilibrium suggested by P. Barton. The principle is based on the experimentally established successive exsolution of secondary minerals and the associated varying equilibrium of water containing deposited minerals under the conditions in the entire nonequilibrium system.

The SOLMINEQ.88 thermodynamic program [11] kindly provided us by our American colleague Y. K. Kharaka (United States Geological Survey) was applied in order to model the hydrogeochemical processes. SOLMINEQ.88 uses as initial data for the modeling results of chemical analysis of water in the form of analytic concentrations (expressed in terms of mg/liter), pH values, which under our conditions vary from top down in the column from 8.3 to 7.1, temperatures measured in the boreholes (under our conditions, 5-8°C), and the standard pressure (1 bar). We calculated the following quantities: (1) forms in which we find ions and neutral molecules, for example Ca^{2+} , CaHCO_3^+ , CaCO_3^0 , etc. that actually exist in subsurface waters as well as their concentrations; (2) the activity coefficients and activity of particles present in the solution; in order to calculate the activity coefficients of the ions in the case of highly mineralized water (> 50 g/liter) we introduced the Pitzer correction factor, which is provided in the program; (3) the degree of saturation of subsurface water with the solid phases we were interested in (calcite, dolomite, gypsum, halite). By degree of saturation we understand the logarithm of the ratio of the products of the activities of the free ions in a solution corresponding to this mineral (PAI) to the logarithm of the thermodynamic solubility product of this mineral (SP). Thus, if $\log \text{PAI}/\log \text{SP} < 0$, the solution is unsaturated, and if $\log \text{PAI}/\log \text{SP} > 0$, it is saturated or supersaturated with respect to the particular mineral. The computation error when using the program amounts to 0.05 logarithmic units. The following thermodynamic quantities in the solubility product are stored in the program: for calcite, $10^{-8.395}$; for dolomite, $10^{-17.784}$; for gypsum, $10^{-4.622}$; and for halite, $10^{1.525}$ (values of the solubility products for calcite of $3.3 \cdot 10^{-9}$ and for dolomite of $2 \cdot 10^{-17}$ were employed in the monograph [3]).

The principal inaccuracy in the chemical analysis of subsurface waters introduced into the program is due, we believe, to the pH value (the time from extraction of the water samples from the borehole to their arrival at the laboratory ranged from several hours to a few days). It is difficult to estimate this inaccuracy.

Engineering Geology and Geoecological Scientific Center, Russian Academy of Sciences (Moscow). Institute of Geology of Komi Scientific Center, Ural Division, Russian Academy of Sciences (Syktyvkar). Translated from *Litologiya i Poleznye Iskopaemye*, No. 2, pp. 78-85, March-April, 1994. Original article submitted November 19, 1992.

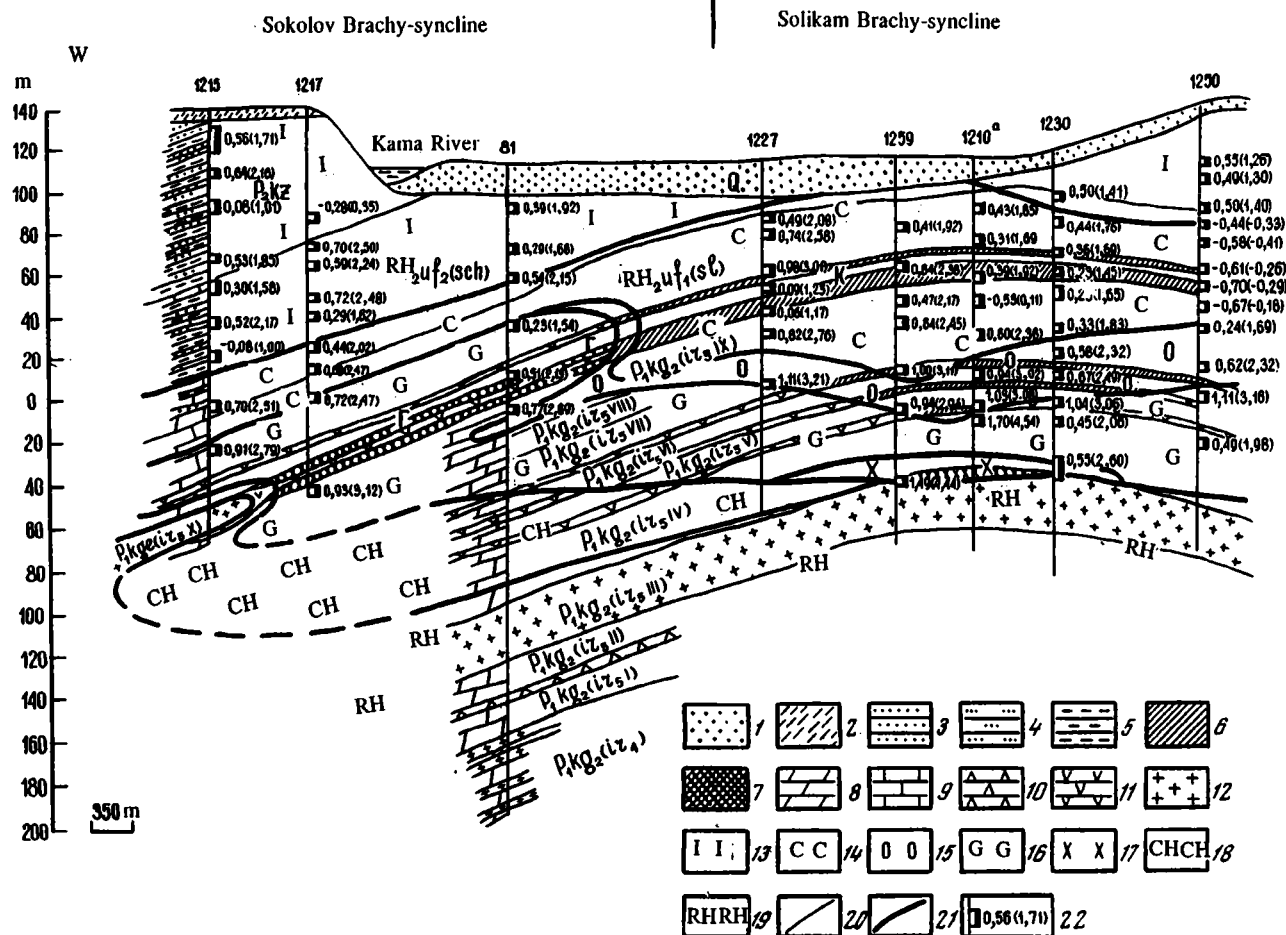


Fig. 1. Degree of saturation of subsurface water with calcite and dolomite (results of thermodynamic modeling of hydrogeochemical processes using the SOLMINEQ.88 program). The profile is taken transverse to the valley of the Kama River above the city of Solikamsk. 1-12: lithological description of rocks (1, sand; 2, loam; 3, sandstone; 4, siltstone; 5, claystone; 6, brecciated clay-marl; 7, brecciated clay-dolomite; 8, marl; 9, limestone; 10, anhydrous gypsum; 11, gypsum; 12, rock salt); 13-19, composition of mineral filler in rock fissures (13, ferric and manganese hydroxide together with calcite; 14, calcite; 15, no mineral filler in open fissures; 16, fibrous gypsum; 17, chalcedony together with microcrystalline gypsum; 18, colorless halite; 19, rose halite together with chalcedony and microcrystalline gypsum); 20 and 21, boundaries (20, lithological-stratigraphic boundary; 21, interface between zones in which the mineral filler in the rock fissures differ); 22, interval within which the hydrogeological experiment was carried out (the first figure is the degree of saturation of the subsurface water with calcite and dolomite (saturation expressed in mg/liter is given in parentheses, with plus indicating that the water is supersaturated, and minus that it is unsaturated)).

The region we are studying is part of the central portion of the Solikam basin of the Cis-Ural foredeep and includes the Sokolov brachy-syncline and the Solikam brachy-syncline (Fig. 1). In the column of the Sokolov brachy-syncline the following minerals fill the rock fissures (moving from top down in the section, but disregarding the age of the rocks): ferric and manganese hydroxide together with calcite, fibrous gypsum, colorless halite, and rose halite together with chalcedony and microcrystalline gypsum. No colorless halite is found in the geological section from the Solikam brachy-syncline. Moreover, here there is a zone beneath the upper boundary of the fibrous gypsum where there is no mineral fill in the open fissures, while over the rose halite roof a zone is found in which open fissures of marl are sometimes filled with fine chalcedony flakes and incrustations of microcrystalline gypsum but only along the margins.

Depending on the composition of the mineral filler in the fissures, the degree of colmatage of the fissures differs markedly, whence the varying permeability of the rock. Thus, siltstone, claystone, sandstone, limestone, and marl together with intercalations of brecciated clay-marl, the fissures in which are filled with ferruginous-manganese compounds and calcite, are permeable (according to data taken from trial wells, the filtration coefficient of k rocks exceeds 0.1 m/day and is usually in the range 1-10 m/day). In the zone where the fissures are filled with fibrous gypsum the rocks (limestone, marl, gypsum with intercalations of brecciated clay-dolomite) are relatively water-resistant ($k < 0.05$ m/day). The rocks (marl, gypsum, anhydrous gypsum, rock salt) that are found in the zones of colorless and rose halite ($k < 0.005$ m/day) are virtually impermeable. In the zone where the fissures are filled with chalcedony and microcrystalline gypsum, the rocks (marl, gypsum, brecciated clay-dolomite) are permeable ($k > 4-17$ m/day). Thus, the interfaces between zones in which the fissures that intersect the lithological-stratigraphic boundaries are filled with mineral fillers with different compositions partitioning the geological section of the area of the Upper Kama into several water-bearing and water-resistant horizons.

Within the first (counting from above) water-bearing horizon confined to the Sokolov brachy-syncline, the chemical composition of the subsurface waters that are drained by the Kama River varies gradually with depth from a mixed hydrocarbonate cation composition with mineralization M in the range 0.2-0.5 g/liter through a composition of sodium sulphate and sodium chloride (M in the range 1.0-30.0 g/liter) up to a composition of sodium chloride (M in the range 30-130 g/liter). In the geological section from the first water-bearing horizon of the Solikam brachy-syncline the composition of the subsurface water varies from a mixed hydrocarbonate cation composition (M in the range 0.19-0.5 g/liter) to sulphate-chloride-sodium compositions (M in the range 1-50 g/liter). In the second water-bearing horizon, which extends solely within the Solikam brachy-syncline, the subsurface waters have a sodium chloride composition with mineralization in the range 223-312 g/liter.

Previously, one of the present authors (L. V. M.) demonstrated [4] that the new geological boundaries, i.e., interfaces between zones with different secondary fissure minerals, that were discovered for the first time in the Upper Kama region are, properly speaking, hydrogeological boundaries both in terms of significance (they subdivide the column into water-bearing and water-resistant horizons) and in terms of origin (they are related to the chemical and dynamic activity of the subsurface water). The creation of infiltration-epigenetic mineral zonation in the persalt rock mass of this region was also considered in this study.

It is now important to study this complicated, briefly described natural system in terms of hydrogeochemistry so as to be able to assess the contemporary and future direction of mineral diffusion and deposition processes.

Results of thermodynamic modeling using the SOLMINEQ.88 program are presented in Fig. 1, which also shows the saturation of subsurface water with calcite and dolomite. All the samples of water, except for several samples taken from borehole 1250, which is situated closest to the recharge region of the water-bearing horizons, proved to be calcite- and dolomite-saturated, moreover the degree of saturation of the water proved to increase with depth. In order to compare the modeling results with the actually present solid phases, we resorted to data of chemical analyses of ~600 rock specimens taken from eight of the boreholes that had been subjected to continuous, leaf-by-leaf sampling. The calculation of the weighted-mean chemical composition of the rocks in the case of nearly each of the stratigraphic bands of the saline-marl series of the Irenian horizon of the Kungurian stage demonstrated [5] that the carbonate-clay rocks (marl, clayey limestone) found in the zone where the calcite is developed in fissures prove to be calcitized, partially dedolomitized, desulphatized, and lacking some of the indissoluble residue by comparison with rocks whose fissures were filled with fibrous gypsum. These changes in the rocks are obviously due not to the primary sedimentation conditions (the sampled boreholes are situated several hundred meters apart), but to the geochemical activity of the subsurface waters in the most recent stage of geological development of the region. Microscopic investigation of microsections of marl, specimens of which were taken from the zone characterized by calcite distributed in the rock fissures showed that finely dispersed carbonate-clay mass is replaced at some of the sites by secondary calcite.

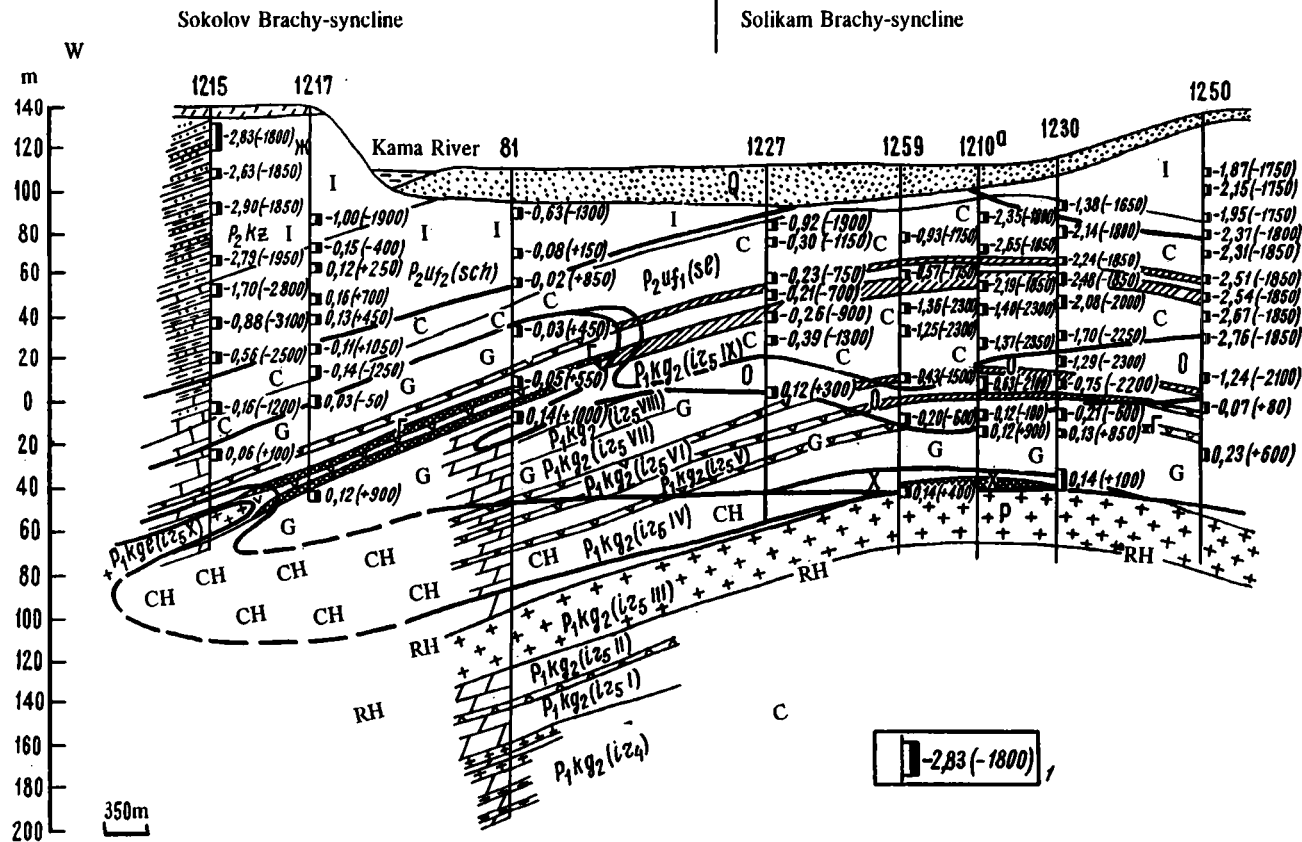


Fig. 2. Degree of saturation and saturation of subsurface water with gypsum: 1, interval within which the hydrogeological experiment was carried out (the first figure is the degree of saturation determined using the SOLMINEQ.88 program, with the figure in parentheses indicating the saturation (expressed in mg/liter) given in [1], with plus indicating that the water is supersaturated, and minus that it is unsaturated). For an explanation of the other notation, see Fig. 1.

Thus, results of thermodynamic modeling and the actual data diverge somewhat. Whereas everything is satisfactory in the case of calcite, there are inconsistencies in the case of dolomite that are best explained by kinetic factors. In fact, in one monograph by S. R. Krayonov et al., it was concluded that " ... the modeling that has been reported here demonstrated the inadequacy of an exclusive reliance on the thermodynamic analysis in order to explain such complex geochemical processes as dolomitization. Our understanding of the geochemistry underlying the formation of such complex and multi-component solid phases as dolomite will not be complete without a kinetic analysis of their formation" [3, p. 218].

In general, the relationships that have been discovered between the solubility and abundance in nature of calcite and dolomite are rather vague, and there are a number of mutually exclusive points of view on this question [6, 7, 9, 10].

In the second (counting from above) water-bearing horizon of the Upper Kama region, the fissures in this horizon are only incompletely filled with chalcedony and microcrystalline gypsum. Here the subsurface waters are saturated with respect to both calcite and dolomite. This is attested to both by calculations using SOLMINEQ.88 as well as by the geological data. Anhydrous brecciated dolomite clays that abruptly replace rock salt seams are formed in this horizon. In the first water-bearing horizon, which we spoke of earlier, brecciated clay-marl is abundant. The chemical composition of these two types of clay are presented in [5].

Figure 2 shows the degree of saturation and the saturation of subsurface water with gypsum, calculated using SOLMINEQ.88 and a method once proposed by one of the present authors (V. P. Z) [1]. In only seven of the 69 samples shown in Fig. 2 did the saturation sign differ. In these seven samples the extent of the deviation from equilibrium was either within the range of the modeling error using the program or within the range of the computation inaccuracy (on average, the deviation between the computed and experimental calculations was around 5%) using the method of [1]. The two methods we are using may, therefore, be said to be in satisfactory agreement.

Except for several samples taken from boreholes 1217 and 81, both of which are confined to the Sokolov brachy-syncline, it turned out that water from the first water-bearing horizon is not saturated with gypsum. It became clear, moreover, that the upper boundary of distribution of fibrous gypsum in the fissures is a surface which is also the boundary in the hydrogeochemical medium that demarcates subsurface water that is unsaturated with respect to this mineral versus subsurface water that is supersaturated. One exception that could be cited is that of the most highly warped synclinal structures at a distance from the subsurface water recharge regions where water that is supersaturated with respect to fibrous gypsum is found directly above the fibrous gypsum zone. In other words, the upper boundary of the fibrous gypsum zone, which coincides with the base of the first water-bearing horizon, constitutes, within the anticlinal structures, a contemporary diffusion surface of this mineral, and within the highly warped synclinal structures, a surface for the formation of fibrous gypsum. In the geological columns of the anticlinal uplifts, this surface is displaced downward through the column, though in the most depressed districts of the synclinals, upwards through the column as a consequence of precipitation of gypsum in sediment from saturated and supersaturated water. The rate of this process is not known, though it is apparently comparable with the rate of contemporary vertical differentiated tectonic movements that are opposite in direction by comparison with the hydrogeochemical processes.

In the second water-bearing horizon, which is distributed only in the Solikam brachy-syncline, the subsurface water is supersaturated with respect to gypsum. We can characterize both the water-bearing horizons by the fact that the subsurface water is unsaturated with respect to halite. Whereas the former assertion is demonstrated by data from thermodynamic modeling and the results of calculations arrived at using the method of [1], the latter assertion is proved only by means of SOLMINEQ.88.

It is likely that the lower boundary of the fibrous gypsum zone, which is the roof of the second water-bearing horizon, is displaced downward through the geological column as a consequence of its accretion as a result of the formation of this mineral. At the same time, the upper boundary of the rose halite zone, which is the roof of the second water-bearing horizon, is also displaced downward in the geological column as a consequence of the diffusion of streaky rose and stratified halite.

Above the zone in which colorless halite is distributed in the rock fissures (in the Sokolov brachy-syncline), the hydrogeochemical setting remains in question, since it is practically impossible to extract reliable samples of water from the water-resistant horizons by means of existing technical equipment. We can only assume that, based on the contemporary tectonic setting (subsidence), the upper boundary of the zone of colorless halite is displaced upwards in the geological section.

In conclusion we wish to take note of one of the principal conclusions in a recently published monograph by S. I. Smirnov, to the effect that " ... all the properties and signs of subsurface water vary in space, as a rule continuously,

without any nodal points. But this must mean that there do not exist any objective quantitative or qualitative criteria by means of which the hydrogeochemical structure of the basin could be partitioned into hydrogeochemical zones. The boundaries of these zones are inevitably provisional and subjective" [8, p. 212]. On the basis of the material that has been presented in this article, it may be assumed that such sharp hydrogeochemical boundaries would nevertheless have to exist in a section from the basins. These boundaries would constitute the interfaces between subsurface water that is unsaturated versus subsurface water that is saturated with respect to the principal hydrogenous minerals (calcite, dolomite, gypsum, halite). Such interfaces possess objective quantitative and qualitative (including mineralogical) criteria by means of which the hydrogeochemical structure of the basin present in a number of zones may be partitioned, though these zones may be characterized by subsurface waters possessing a uniform composition. It is only important that mineralogical sampling be detailed, and that the methods of thermodynamic modeling of the direction of the hydrogeochemical processes be made more accurate.

* * *

In the present study we have arrived at the following conclusions:

1. SOLMINEQ.88 is an effective tool for thermodynamic modeling of the direction of hydrogeochemical processes between natural water and hydrogenous minerals, since the results obtained with the use of this method are confirmed by mineralogical observations.

A method of determining the degree of saturation of natural water with respect to gypsum that was developed earlier [1] gives results that are comparable with computer-aided thermodynamic modeling, is quite easy to use, and may be employed as an approximation method, particularly when the investigators lack expensive computer programs and computer equipment.

2. The interface between zones in which the mineral filler of the fissures that intersect the lithological and stratigraphic divisions possess distinct compositions are, at the same time, hydrogeochemical boundaries that sharply subdivide the hydrogeochemical structure of the persalt rock mass of the Upper Kama region into subsurface water that is unsaturated with respect to certain secondary hydrogenous minerals versus subsurface water that is saturated with respect to these minerals. Only on the basis of a careful documentation of core samples from the boreholes together with investigation of the mineral filler of the fissures is it possible to arrive at a preliminary assessment of the direction of the hydrogeochemical processes that occur between subsurface water and calcite, gypsum, and halite. Thus, rocks in which the fissures are filled with calcite usually contain water that is saturated with respect to calcite and unsaturated with respect to gypsum and halite. Rocks in which fissures are filled gypsum include water that is saturated with respect to gypsum and calcite and unsaturated with respect to halite. The one exception that could be cited is that of the highly warped syncline structures. Subsurface water saturated with gypsum often occurs in geological sections taken from these structures, above the upper boundary of the zone in which fibrous gypsum is distributed in the fissures,

3. Highly warped synclinal structures would appear to be the most stable and safest sites in the Upper Kama region for locating heavy industrial and hydraulic engineering equipment as well as potash mines. Here there is no secondary (counting from above) water-bearing horizon with subsurface water that is not saturated with respect to halite and, moreover, the thickness of the water-resistant rock mass is substantially greater due to the presence of water-resistant rocks in which fissures are completely filled with colorless halite and, higher up in the geological section, with fibrous gypsum.

REFERENCES

1. V. P. Zverev, Hydrogeochemical Investigations of the Gypsum -- Subsurface Water System [in Russian], Nauka, Moscow (1967).
2. V. P. Zverev, "Kinetics of the interaction of water and rock at the principal stages of the sedimentary process," *Izv. RAN, Ser. Geol.*, No. 2, 105-113 (1992).
3. S. R. Krainov, Yu. V. Shvarov, D. V. Grichuk, et al., *Methods of Geochemical Modeling and Prediction in Hydrogeology* [in Russian], Nedra, Moscow (1988).
4. L. V. Migunov, "Hydrogeological boundaries in deposits of persalt complexes of the Upper Kama and Nurek ore deposits," *Izv. Akad. Nauk SSSR, Ser. Geol.*, No. 8, 116-123 (1986).

5. L. V. Migunov, "Problems in the lithology and stratigraphy of the Solikam trough in light of hydrogeochemical data," *Litol. Polezn. Iskop.*, No. 1, 136-141 (1992).
6. A. I. Perel'man, *Geochemistry of Epigenetic Processes (Zone of Hypergenesis)* [in Russian], Nedra, Moscow (1965).
7. Ya. K. Pisarchuk, "Lithological and geochemical transformations of halogene-carbonate formations in a zone of hypergenesis," *Litol. Polezn. Iskop.*, No. 3, 105-120 (1975).
8. S. I. Smirnov, *Historical Hydrogeology* [in Russian], Nedra, Moscow (1991).
9. D. S. Sokolov, *Basic Conditions in the Development of Karst* [in Russian], Gosgeoltekhizdat, Moscow (1962).
10. N. M. Strakhov, *Limestone-Dolomite Facies of Contemporary and Ancient Reservoirs* [in Russian], *Tr. Geol. Inst. AN SSSR. Geol. ser.*, Vol. 124, No. 45 (1951).
11. Y. K. Kharaka, W. D. Gunter, P. K. Aggarwal, et al., *SOLMINEQ.88: A Computer Program for Geochemical Modeling of Water-Rock Interactions*, *Wat.-Res. Inv. Report 88-4227*, U.S. Geological Survey, Menlo Park (1989).
12. K. S. Pitzer, "Thermodynamics of aqueous electrolytes at various temperatures, pressures, and compositions," *Am. Chem. Soc. Symposium*, No. 133, 451-466 (1980).

FORMATION CONDITIONS OF ORE-BEARING FACIES AND DETRITAL ORES OF THE KORBALIKH POLYMETALLIC PYRITE DEPOSITS, ALTAI ORE RANGE (RUDNYI ALTAI MTS.)

A. G. Kuznetsov, A. G. Zlotnik-Khotkevich,
and V. M. Chekalin

UDC 551.21:553.311.661.2

Volcanic-sedimentary rocks of the Korbalkhinsk polymetallic pyrite deposits of the Altai Ore Range accumulated at the foot of an ancient underwater volcano over strongly dissected underwater bottom. The enclosing rocks represent a variety of facies. Detrital ores concentrated in the channel of an ancient canyon and were represented by slump breccia and proximal turbidite lithofacies. As a factor of their distance from the massive ore bodies, they alternate with each other. The composition and structure of the ore fragments indicated complete identity with the massive ores. This demonstrated that detrital ores accumulated nearly synchronously with the enclosing rocks.

The Korbalkhinsk polymetallic pyrite deposits in the Zmeinogorsk region of the Altai Ore Range have been under study for over thirty years. Specific localities favored for ore development, characteristics of geological structures, ore mineralogy, metasomatic alterations around ores, as well as genetic problems had been described in detail in numerous publications [2, 9, 5]. However, disagreements persist as to the ages of the ores and their formation conditions. Some favored pre-fold [10, 11], others, post-fold [1] ages, metasomatic [1], and polygenetic [10, 11] ore development. These disagreements were mostly related to the fact that in past research little attention had been paid to the different facies types of various ore deposits and to the enclosing volcanic-sedimentary rocks. Only recently did data emerge on the origins of the widespread ore breccias. Convincing proof for the detrital nature of ore matter [10] included: truncation of banded polymetallic ores by rock fragment boundaries, the absence of connecting ore bodies that lead from surrounding cement to the fragments, as well as primary concentric zonation of fragments and rock fragments, in different stages of replacement by sulfides. These data helped to identify the age of ore formation and of the enclosing rocks.

We attempted to compare the depositional facies of detrital ores and the enclosing volcanic rocks on the basis of detailed studies of structural characteristics, composition, and granulometry, to identify the age of ore mineralization. This helped in reconstructing depositional setting and processes. The results help in solving genetic problems in other Altai ore Range deposits as well. The present paper was based on deep drill data, utilizing the study of the most representative drillholes.

The Korbalkhinsk deposit occurs in the southwest limb of the Bystrushinsk Synclinorium in the Zmeinogorsk ore district. A detailed account of the geological composition of the ore deposit and its surroundings has been published [1]. Various Middle and Upper Devonian rocks represent the section. Middle Devonian (upper Zhivetsk) rocks of the subore Shipunovsk Formation occur in the upper interval of interlayered bituminous-limey argillites, tuff-bearing aleurolites, tuff-sandstones, and acidic crystalloclastic tuffs. Rocks of ore-bearing Davydovsk Formation belong to the Upper Devonian Fransk Stage. They occur in basalt, rhyolite (liparite), and terrigenous formations [8]. Five subunits [3] have been distinguished on the basis of dominant volcanic rock components:

(1) *Subore horizon*. Varied detrital crystalloclastic rhyolite porphyry tuffs with tuff-sandstone and clayey aleurolite layers (Fig. 1). More than 100 m thick.

(2) *Ore Horizon* (Fig. 1). Thoroughly interlayered bituminous argillites, aleurolites, tuffs of rhyolite (liparite)-dacite porphyries and sediment breccias with numerous ore clasts, polymetallic and pyrite ores. The contacts between this horizon and the under- and overlying rocks are sharp. Thickness: 10-100 m.

(3) *Lavas, lava-breccias, amygdaloidal porphyries*, rarely thin bedded tuff layers of the same composition. Ore clasts occur in rocks at the base of the deposits in the northwest area and decline in number southeastward. Thickness: 30-400 m.

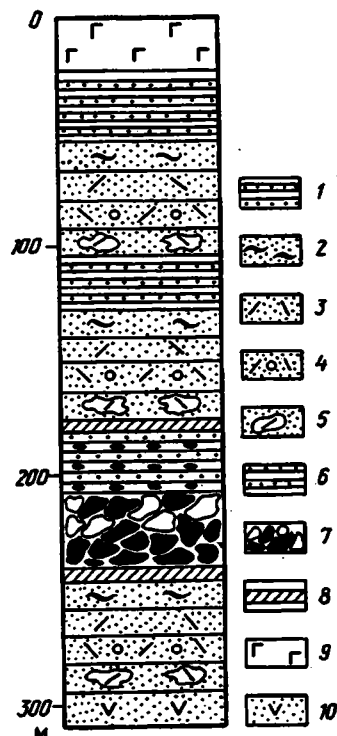


Fig. 1. Generalized diagram of subore and ore-bearing horizons of the Korbalkhinsk Deposit: 1) contourites and turbidites; 2-5 liparite-dacite porphyry tuffs [2 – massive aleuropelites; 3 – parallel-layered fine detrital and sandy; 4 – parallel-layered detrital pumice matter of different grain sizes; 5 – massive graded]; 6) ore clasts in volcanic-sedimentary rocks; 7) ore breccias; 8) chloritized zone; 9) basalt porphyry lavas of the ore-covering horizon; 10) rhyolite porphyries of the subore horizon.

(4) *Frequent interaction between fine-detrital, acidic and basic volcanic porphyries.* Thickness of the horizon increases downdip toward the northeast and northwest from 100 to 700+ m.

(5) *Rhyolite and rhyolite-dacite rocks of finely disseminated and aphyric porphyry, with rare, thin aleurolite layers.* The upper boundary was eroded. Total thickness exceeds 500 m.

The paleostructure analysis of Davydovsk Formation rocks indicate that ore accumulation took place in the peripheral zone of the slope of a large paleovolcano where intersected by faults of various orientation [9].

ROCKS OF THE ORE HORIZON

The study of rocks in the second (ore-bearing) horizon, indicated the abundance of volcanic-sedimentary rocks and detrital ores, often-associated with gradual transitions. This was caused by ratio variations of detrital ore and nonore matter. This fact suggests that a single mechanism accounted for the accumulation of ore-bearing rocks and detrital ores. However, detailed analyses of all different sediment characteristics and identification of their genesis are required for solving this problem.

Components of the ore-bearing rocks belong to the sedimentary-volcanic and volcanic-sediment categories. The first includes rhyolite (liparite)-dacite porphyry rocks that bracket the ore deposit.

The second group consists mostly of epiclastic edaphic matter and minor (maximum 5%) admixtures of biogenic components [7]. These deposits occur between the tuff beds and within the ore deposit.

Rhyolite (liparite) -Dacite Porphyry tuffs. Based on our study of the composition and granulometric analysis of the sediments, the quantitative relationships between components, the degree of particle rounding and layering of acidic tuffs, five rocks types have been identified. They include cyclites (cyclic units) with the following spatial distribution:

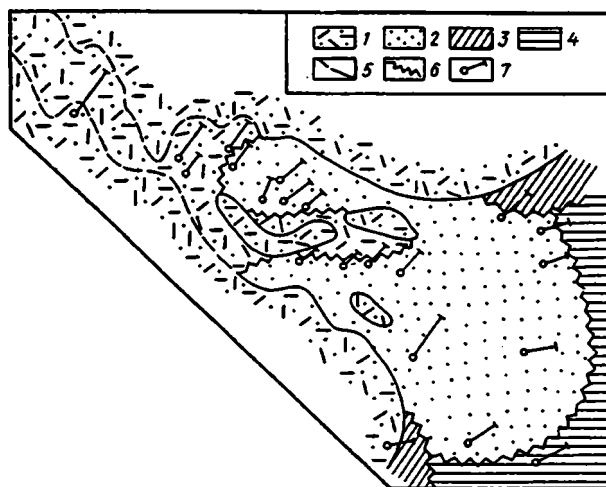


Fig. 2. Sedimentary-volcanic and volcanic-sedimentary rock distribution in the ore-bearing horizon; horizontal projection of ore body: 1) rhyolite-dacite porphyries (underwater pyroclastic flow deposits); 2) edaphogenic turbidites; 3) contourites; 4) argillites (hemipelagic clays); 5) contours of projected ore deposits; 6) facies transition boundaries; 7) drillhole projections on horizontal plane.

Coarse-grained, graded tuffs occur at the base. Upward, they grade into three parallel-bedded volcanic tuff varieties: poorly sorted, gravelly-coarse sandy, and psammitic, fine grained tuffs. Massive aleurolitic tuffs cap this sequence. Fine-grained types are often absent.

Graded, poorly sorted tuffs consist of rhyolite (liparite)-dacite porphyry fragments. Of irregular, angular shapes, they are densely packed. Cement is almost absent. Boulder- and pebble-sized clasts. The largest fragments occur at the base of the bed. Lenses and pockets of meandering outlines are composed of fine-detrital rhyolite tuff from the underlying subore horizon, or argillites. Fragment size diminishes upward. Layering is indistinct. The cement consists of shards of strongly chloritized volcanic glass and plagioclase crystals. The lower contact of massive graded tuffs is sharp, uneven, with indications of truncated beds and fragments dragged over the bottom surface. Toward overlying, parallel-layered tuffs, the contact is gradational.

Parallel-layered, gravelly-pebbly tuffs consist mostly of pumice fragments. They differ in their reverse grading within the pumice layers. Crystalloclastic matter also occurs; its concentration increases in the lower beds. Significant numbers of shards of chloritized glass occur in the upper beds.

Parallel-layered Psammitic tuffs contain quartz and plagioclase grains, with fresh shards, sand-sized pumice fragments, and sericite-chlorite cement. Crystalloclastic particles concentrate at the base of one 5-10 cm thick layer, while pumice matter occurs mostly in the upper interval.

Parallel-layered fine-detrital tuffs often are represented by thin, unweathered crystalloclastic layers. The quartz and plagioclase clasts are of aleurolitic size. These layers alternate with aleurolitic-pelitic beds of chloritized volcanic glass. Locally, layering is destroyed by cross-cutting erosional features.

Massive aleurolitic-Pelitic tuffs that are less frequent, complete the cycle. Due to horizontal bedding, reduction in particle size and relative concentration of crystalloclastic matter, gradation is smooth toward this subunit. The transition starts in the upper part of the preceding horizon. The rock lacks bedding and consists almost completely of chloritized volcanic glass shards, mostly of forked shapes. As earlier shown, the five tuff types occur in a well-defined succession in the section and are gradational toward each-other. Particle size, density declines upward in the sequence; pumice and pelitic-sized volcanic glass shards begin to dominate. Composition changes are reflected by structural characteristics.

Various authors have repeatedly described associated acidic tuffs in the Ural (I. V. Khvorova, V. T. Frolov, Gavrilov, and A. G. Zhabin) and Japanese [12] island arc complexes. Yamaga attributed their formation to underwater pyroclastic flows at shallow depths and the transport of eruption products to deeper water zones. Certain fine-grained tuffs are known to have formed by ashfall [6]. Particle sorting, according to the authors was influenced by prolonged trans-

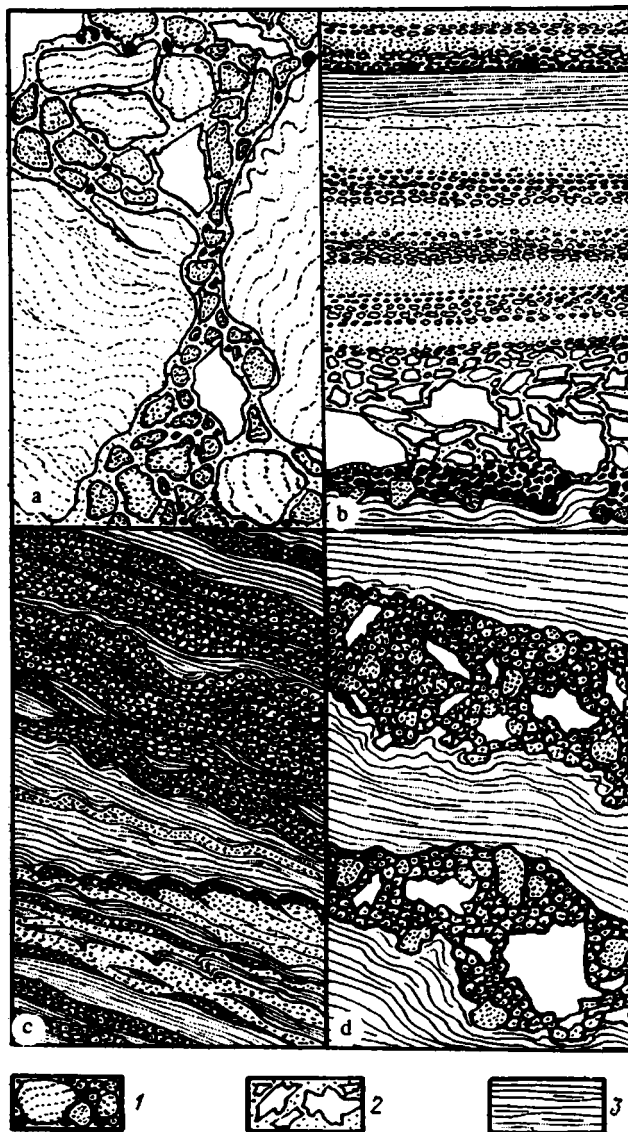


Fig. 3. Detrital ore structures in Korbalkhinsk Deposit: a) slump breccias of different clast sizes. The clasts represent ore and nonore matter. No magnification. Drillhole 485 (583.3 m depth); b) edaphogenic turbidites with small ore-clast groundmass. No magnification. Drillhole 492 (197 m); c) contorted-layered, floating fine-grained ores with chlorite cement. $1.5 \times$ magnification. Drillhole 429 (184 m); d) alternating layers of poorly sorted ore- and volcanoclasts of varying dimensions in argillites (grain flow deposits). No magnification. Drillhole 485 (604.6 m). 1) ore clasts; 2) edaphogenic and epiclastic matter of different composition and dimensions; 3) argillites.

port and settling in water. Depending on water depth, eruptive forces and current direction, the pyroclastic flow may have extended 30 km from the eruption center [14]. The predominance of medium- and fine-grained detrital particles in the Korbalkhinsk tuffs was related to the distance of their distribution areas from the eruption center. Facies variations were caused by the significant distance of water transport. Filatov and others [9] believed that the ore-bearing pyroclastic Korbalkhinsk deposits accumulated at a distance of 3.5-5 km from the eruption center.

Volcanic–Sedimentary Deposits. This sequence was formed by the previously noted pyroclastic flow (Fig. 1). On the basis of granulometry, bedding type, and component interrelationships, this unit in the Korbalkhinsk deposits is subdivided into three categories:

Argillites. Massive sedimentary structures characterize argillites. They consist mostly of Mg–Fe-chlorites (over 90% of the total clay mineral content), as well as of small unoriented quartz, K-feldspar, and oligoclase grains, biogenic matter (radiolarians, fish bone fragments), and relicts of chloritized volcanic glass shards. In addition, increased organic carbon content* (1.5–2%) characterizes them (analyses by DEI TsNIGRI, Tula). Thickness of the massive argillite beds do not exceed a few meters.

These rock characteristics apparently were associated with deposition in relatively deep waters. Bottom currents were weak, the depositional facies hemipelagic.

Aleurolites consist of frequently interlayered, few millimeter thick laminae of well sorted dark-gray aleurolite with black aleuoropelitic argillite. The layers locally wedge out or are lenticular. In addition to the clay cement, numerous quartz, plagioclase, volcanic glass grains, biogenic carbonate fragments, siliceous sponge spicules and rounded ore clasts occur in the aleurolite layers. Particles are oriented parallel with the layering. Few tens of meters thick in the ore horizon, the deposits apparently were contourites, accumulated at the toe of or steps cut into the paleovolcano slope.

Graded pebbly-aleurolitic layers occur among aleurolites and argillites (beds, 0.5–10 cm thick). They consist of rhyolite (liparite)–dacite porphyry fragments, chloritolith, quartz, plagioclase and ore clast grains, as well as individual biogenic fragments (fish bones, sponge spicules, bryozoans). The lower contact of each layer is abrupt and displays an erosional break. The unconformity surfaces are overlain by coarse, gravelly–sandy, angular rock fragments with partially rounded ore clasts. They mutually overlap in a unidirectional scalelike pattern. Upward in the section, the clasts gradually diminish in size. Parallel bedding develops. Higher in the section, a new erosional surface appears, associated with coarse detrital matter. Ore and nonore chloritoliths possess a number of similar general characteristics. Ore clasts and chloritolith fragments formed by underwater weathering of massive ore deposits and represent edaphogenic matter that was rounded and disintegrated in transport. Partially rounded rhyolite (liparite) and dacite tuffs may have formed by underwater rock weathering on the seafloor and reworking along with edaphogenic matter. Matter from unconsolidated underwater pyroclastic flows served as source of the unweathered and partly rounded sandy-aleurolitic volcanoclasts. Their secondary reworking formed the epiclastic matter.

Combined characteristics (layering, grading, current marks and erosional features) of graded and parallel-laminated layers represent the two lower cyclite elements of edaphogenic proximal turbidite.

Argillites, aleurolites and graded pebbly-aleurolitic layers in the ore-bearing horizon generally overlie the finest detrital tuffs of the earlier deposited pyroclastic flow. They, in turn, are overlain by massive coarse-detrital tuffs of the next younger flow (Fig. 1). The lower contact of the volcanic–sedimentary rocks is indistinct. In a number of drillholes massive silty-pelitic tuff alternates with argillites. This is indicated by gradual reduction of volcanic glass shards to pelitic size and simultaneous appearance of identical sized, highly angular quartz and plagioclase fragments; also individual radiolarians and fish bone fragments. The upper contact of argillites and aleurolites is sharp and uneven toward the tuffs, with indications of loosened rock consistency. Marks indicate that large fragments were dragged over soft sediment surfaces. Irregularly shaped argillite fragments occur occasionally in the lower, massively graded tuff bed.

Laterally, from NW toward the SE, the tuff and edaphogenic turbidite grain sizes diminish gradually in the unit. The coarsest detrital rocks occur in the northwestern and central areas of the deposit. Toward the southeast, they successively alternate with finer detrital turbidites, contourites and hemipelagic clays. The last two occur at the southeast terminus of the ore deposit. (Fig. 2). The lateral and vertical distribution and composition of the previously noted tuff, argillite, and aleurolite units indicate that the pyroclastic flows moved downslope over underwater volcano slopes and formed channel deposits. In downslope direction, the flows incorporated rock fragments from foothill slopes and finally spread over the basin floor adjacent to the volcano. Hemipelagic clays also accumulated here. The thin (few meters) nature of cyclites in underwater pyroclastic flows and absence of effusive volcanic facies may be related to the very low levels of volcanic activity in this region. Because the Korbalkhinsk ore deposit formed in the marginal facies of a large underwater volcano [9], it appears that ravines, incised zones, and ledges on the underwater volcano slopes were the most conducive relief elements for sediment accumulation. The canyon floor was covered by turbidites of essentially of epiclastic

*Analyses performed at OEI TsNIGRI, Tula.

and edaphic matter, transported from the slopes. Contourites settled from boundary currents along banks of the canyon, near its mouth. The massive nature of the primary sedimentary structure and the uniformity of argillites, subsequently formed from contourites, resulted from reduced bottom water current velocities that led to the settling of the finely dispersed sediment particles from the water column. Due to oxidation of large organic matter volumes that entered from the surface waters of high biogenic productivity, bottom waters were largely deprived of oxygen. The dominance of chlorite in the rocks apparently resulted from the presence of volcanic ash that rained down from distant pyroclastic eruption centers.

DETRITAL ORE STRUCTURES AND THEIR GENESIS

Our detailed study of detrital ores that are widespread in ore deposits indicated a strong similarity with tuffs and volcanic-sedimentary rocks in terms of structural features and areal distribution of rock structure categories. This circumstance suggested a uniform formation mechanism. A more detailed treatment of the problem follows.

In terms of its lithology, the Korbalkhinsk pyrite deposit consists of two major units. The northwestern area is dominated by continuous polymetallic ores with massive, mottled, banded and brecciated structures [9]. Massive copper and pyrite sulfide ores are much more limited in abundance. Brecciated ores consist of very large (maximum 50 cm) polymetallic fragments with pyrite cement that may also include chalcopyrite. The fragments are angular, with often similar configuration of adjacent boundaries of the contiguous fragments. This indicates the syneresis origins of the dissecting fracture sets and subsequent cementation by ore matter. Such breccias occur in numerous Ural deposits, developed in the course of syneretic recrystallization, fissuring, and volume reduction [4, 13]. The massive ores are underlain by chloritized rocks (chloritoliths).

The southeast part of the deposit consist of mechanically reworked ore matter. In terms of its structure, it was subdivided into five groups: coarse-detrital breccia, composed of ore and nonore fragments in the ore cement; poorly sorted breccias, with ore and nonore fragments in a nonore cement, graded-layered, medium and fine-grained ores; contorted-layered fine-grained ores and alternating poorly sorted layers, with a wide grain size range, including ore- and volcanoclast matter. In relation to the layered ore concentrate, the breccia in the vertical section usually occupies a lower stratigraphic position.

Breccias of the first type include angular and semirounded fragments of massive polymetallic (5-30-cm particle diameter), rhyolite ("liparite") - dacite porphyries and chloritoliths (maximum 5 cm diameter). The ore cement reaches 50% of the rock volume.

Dominantly rounded ore clasts of pebble-gravel size occur in the *second breccia type*. They consist of rhyodacites and chloritoliths; also sandy-aleurolitic volcanoclasts. The cement is mostly chlorite-bearing, with fresh quartz and plagioclase grains (Fig. 3a). Indistinct layering is occasional in the upper breccia horizons. The particle size becomes somewhat reduced.

In combination, the breccia types form a mutually intergrading, continuous lateral sequence. At one end of the continuum, breccias in the northwestern deposit area display no indications of reworking and massive ore development by spalling. Primarily through decomposition of the massive ore, they grade south- and southeastward into the first, further away, the second breccia types. During transport, the ore fragments became mixed with nonore particles. The absence of distinct layering, good sorting, and of any clast orientation indicates the slump/landslide origins of these deposits. The massive ore succession from northwest toward southeast, involving slump breccias, may have be related to the presence of primary ore deposits in uplift areas and subsequent transport of its fragments southeastward. Poorly sorted, coarse breccias of the first type were laid down in the immediate vicinity of the ore source area. Breccias of the second category, transported to the greatest distance, probably reached the toe of the southeastern slope, at most, the slope bench. Indistinct bedding in the ores indicate that they represented a link between depositional areas and facies that alternated with graded-layered ores. According to the structural features, the indistinctly layered units of the second breccia category greatly resemble the previously described edaphogenic turbidites. They differ in a significantly higher ore content and the poorer sorting values of the fragments. Considering that underwater slumping provided the source of suspension currents, it appears that while slump breccias are composed mostly of edaphogenic and epiclastic matter, underwater weathering, independent of composition played a significant role in the preparation of sediment matter for further reworking by gravity transport processes.

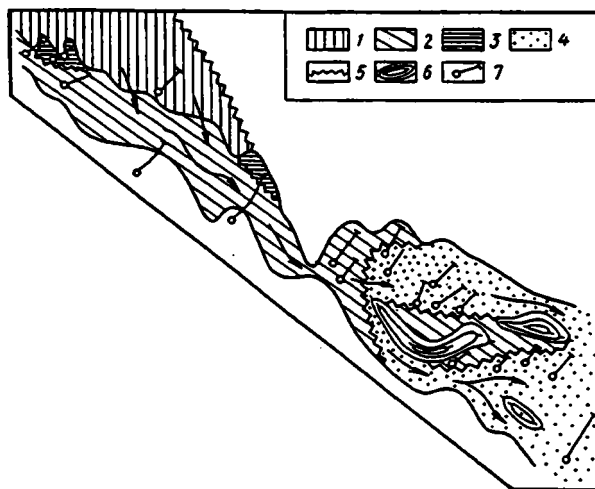


Fig. 4. Distribution of different structural ore types and horizontal projection of commercial ore deposits. 1-4) Ore facies types (1 – massive ores; 2 – slump breccias; 3 – floating ores and ores in grain flow deposits; 4 – ore turbidites); 5) facies transition boundaries; 6) uplifted surface; 7) drillhole projection on horizontal surface; arrows indicate ore fragment transport directions.

Graded-layered ores of the third type are of medium and fine grain size and possess distinct parallel layering. They form cyclites, the lower units of which are dominantly ore-bearing and represent a succession of indistinctly layered, gravelly-pebbly and finely laminated sandy-aleurolitic beds (Fig. 3b). The nonore edaphic matter content does not exceed 30%. The lower, gravelly-pebbly bed has an indistinct graded sedimentary structure and consists of rounded ore clasts and semirounded rock fragment in a chlorite cement. In the upper cyclite units the nonore matter content exceeds 50%. Rounded and semirounded ore clasts, mostly of gravel-pebble size range, are relatively scarce. In sections across an ore clast, on one side of the clast fine sedimentary laminae frequently are buckled down, while on the other side they overlie the ore clast. This indicates that erosion and redeposition of soft sediments have taken place. In relation to the imbricate depositional pattern of turbidite clasts, this defines the transport direction of turbidity suspendates and the transport zone of the ore matter. Data indicate that the graded-layered ores were proximal turbidites.

Convolutelayered, fine-grained ores of the fourth type are composed by alternating thin laminae of well sorted ore matter of sandy and aleurolitic dimensions. These include significant amounts of chlorite (Fig. 3c). The layers are wavy, meandering, sinuous, lenticular, feathery, locally convoluted. Individual large fragments are smoothly enveloped by fine-grained layers. Ores of this type rarely occur in horizons of brecciated ores and are of limited spatial extent. Similar structures apparently formed by the slumping of unevenly saturated sediments over slopes of small channels. Fine-detrital ore matter accumulated here, carried and sorted by currents that descended from elevated areas.

The fifth type includes *gravelly-sandy layers of poorly sorted ore clasts and volcanoclastics* (Fig. 3c). They occur in thin, few cm thick layers, within clayey contourite beds. The lower contact of the beds is uneven and sinuous; the upper, more even and wavy. These deposits in the contourite distribution area formed by deposition from grainflow and were transported from unrelated, diluted granular sediments. Density current deposits are of two categories: deposits formed on slopes and slope-toes, and sediments that settled in ravines and canyon floors. The first is represented by slump breccias that laterally alternate with massive ores; the second, by layered ores, developed on the southeast flank of the ore deposits (Fig. 4). The sorting of detrital matter and definition of the bedding gradually improves, and grain size decreases from northwest toward the southeast. Concurrently, the ore concentration declines from 100%, to 10-15% in the same direction.

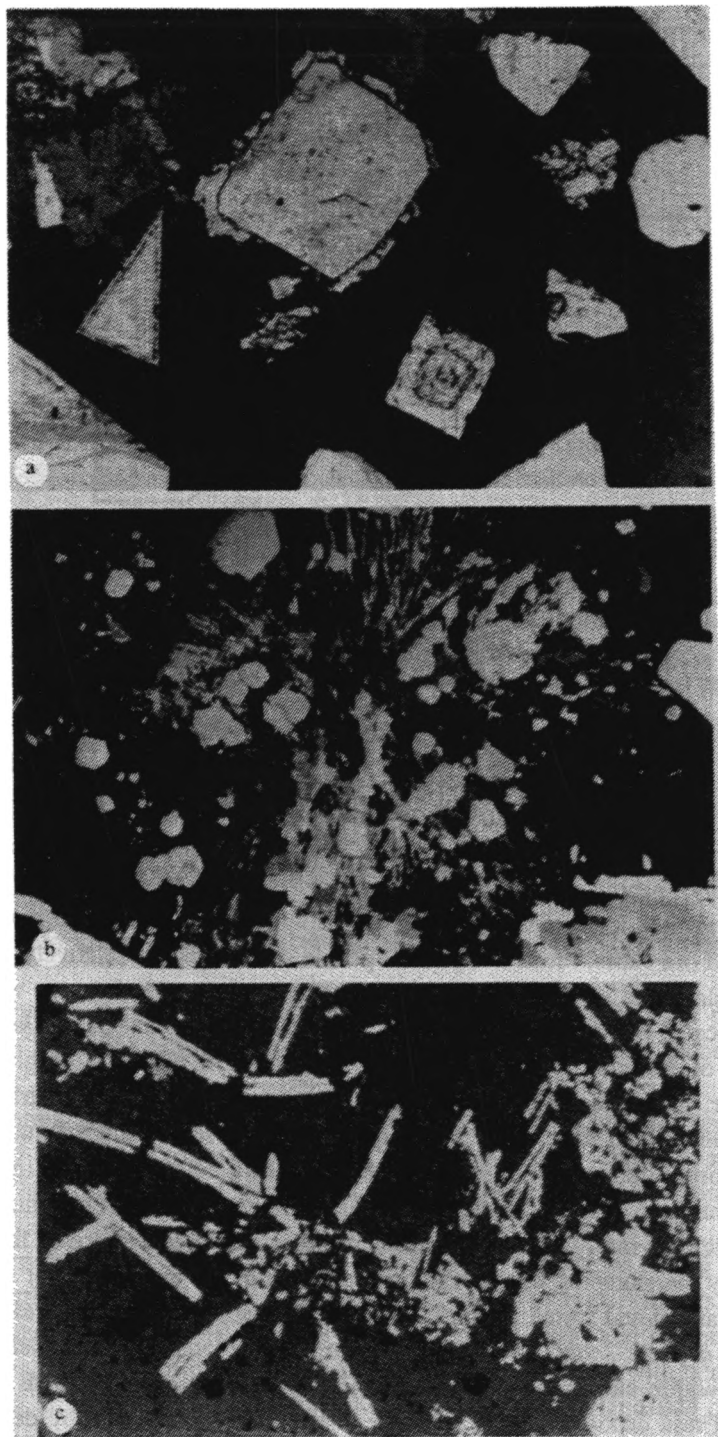


Fig. 5. Ore mineral microphotograph in polymetallic ores, Korbalkhinsk Deposit: a) detrital pyrite crystalloclasts, well expressed zonal growth bands; black: vein mass, polished section; 250 $\times$ magnification. Nitric acid etching. Drillhole 492 (624.1 m); b) radiating marcasite aggregate rays (white) in cementing vein matter (black). Small pyrite crystal clasts (white); gray-sphalerite; light gray: chalcopryrite. Polished section, 250 $\times$ magnification. Drillhole 492 (673.3 m); c) sheathlike lamellar precipitates; d) marcasite pseudomorph (white) along border of residual body (probably fish bone), black: aleurolites, polished section, 500 $\times$ magnification. Drillhole 496a (672 m); e) pyrite crystalloclast (white), pentadodecahedral habit, corroded by sphalerite (gray); rim of older marcasite well visible. Zonal aggregate of metacolloidal marcasite and finely dispersed vein matter in upper right corner. Polished section, 250 $\times$ magnification, etched with nitric acid. Drillhole 406 m (611.15 m); f) pyrite crystalloclasts (white), with marcasite rim growth; black: vein mass, polished section, 250 $\times$ magnification, nitric acid etching. Drillhole 496a (672.95 m).



FORMATION CONDITIONS OF DETRITAL ORES AND ORE-BEARING BEDS

The outline of the distribution area of detrital ores is elongated, meandering, with a narrow northwestern end segment, a wider southeastern terminus, and a narrow middle sector. Massive ores border on detrital ore deposits in the north and northwest. Very limited amounts of mudflow-derived ores occur at the boundary between massive and detrital ores. The northwest and central parts of the deposits include slump breccias. Toward the southeast, slump breccias successively alternate with ore turbidites and hemipelagic clays. Toward the southeast, ores are absent from three areas in the wedge-out zone of the deposits. Partially sorted slump breccias surround two of the areas. These are transitional toward proximal turbidites. This circumstance indicates presence of three local uplifts in the area at the canyon mouth. The ore body and the distribution pattern of ore types of different structures support the earlier conclusions on detrital ore accumulation in canyons. Distribution patterns of detrital ores and their structural alteration also indicate that the canyon mouth had opened toward the southeast. The steep canyon walls in the 80-100 m wide upper reach were instrumental in the filling of the canyon by landslide deposits (Fig. 4).

A narrowed middle course (10-15 m) probably was controlled by resistant rocks that impeded transport of the coarsest detrital material toward the southeast. The canyon widened downstream to 120 m beyond this threshold. Its floor was covered mostly by turbidites. Small topographic rises near its mouth subdivided the canyon into two 10-15 m wide (left and right) marginal distributary channels and a 45-50 m wide middle distributary. The total canyon length was 1400 m; the total width at the mouth, 280 m. Thin suspension units settled unrelated to turbidity transport. As earlier shown [11], deposition of dispersed detrital ore matter progressed from northwest—north, in a southeasterly direction. Transition from slump deposits to turbidites apparently started at the canyon mouth. Sorting improved; grain size and thickness of the cyclite unit declined with increased transport distance. Seismic vibrations of certain suspendate deposits resulted in thixotropic liquefaction of water-saturated ore matter. Slumping and intermixing with unrelated granular sediments took place. These suspendate flows reached the canyon channel.

Due to underwater weathering Processes and gravitation transport, genetic features indicate the uniform formation conditions of ore and nonore deposits. The great variety in deposit types was the result of the mixing of the major sediment components (ore and nonore matter of edaphic and epiclastic origin). The strongly dissected bottom relief; essentially the diversity of sedimentary facies was the other cause.

MINERAL COMPOSITION AND STRUCTURE OF CLASTIC ORES

In establishing the upper age boundary of the massive ores in the northwest part of the deposits, the authors studied the mineralogy and compositional characteristics of ore clasts and mechanically transported detrital ores.

Visual and microscopic studies indicate that polymetallic ore clasts predominate in all detrital ore varieties. Copper and pyrite ores are much less frequent. Pyrite and sphalerite crystalloclasts are ubiquitous. Chloritolith fragment with sulfide impregnation developed in an earlier stage.

Fragments of polymetallic ores are characterized by massive, mottled and banded structures. They are composed mostly of sphalerite, with minor amounts of galena, chalcopyrite, pyrite, and tetrahedrite. Sphalerite aggregates are composed of isometric grains that, due to a color change from honey-yellow to black, are banded. They are oriented along octahedral, rarely, hexagonal crystal prism directions. Chalcopyrite, galena, and tetrahedrite occur mostly in interstices between sphalerite crystals. Chalcopyrite also occurs as liquid (emulsion) inclusions, frequently along sphalerite zones. Pyrite, disseminated in sphalerite is represented by small, well-oriented grains of cubic, cuboctahedral, frequently of skeletal habits.

On certain occasions, fragments of brecciated polymetallic ores occur with veins of metacolloidal pyrite or carbonate, thoroughly impregnated by fine-crystalline pyrite that does not extend beyond the fragment boundaries. The presence of such fragments indicates that brecciation and cementation continued during deposition of massive ores, until burial by overlying rocks. In addition to chalcopyrite, annular pyrite aggregates and xenomorphic tetrahedrite precipitates also occur in cupriferous, essentially chalcopyritic, auriferous ore fragments.

The essentially pyritic fragments consist of fine grained metacolloidal pyrite of concentric zonation. Small amounts of chalcopyrite, sphalerite, galena, and tetrahedrite were found in zonal pyrite aggregates or filled interstices in recrystallized portions.

TABLE 1. Geochemical Characteristics of Pyrites in the Detrital Ores

Sample number	Cu	Zn	Pb	Ag	Sb	As	Mn	Ni	Co	Ba
Pyrite crystalloclasts										
1	0,03	—	0,3	70	—	—	0,3	0,007	0,007	—
2	—	—	0,03	—	—	—	0,01	—	Traces	—
3	0,003	—	0,01	—	—	—	0,01	—	0,01	—
4	>1	1	0,03	70	—	—	0,01	—	0,02	—
5	0,1	—	0,03	—	—	—	—	—	Traces	—
6	0,03	—	0,05	15	—	—	—	—	—	—
7	—	—	0,01	—	—	—	—	—	—	—
8	—	—	0,3	10	—	—	—	0,007	Traces	—
Metacolloidal pyrite in cement										
1	0,3	—	0,5	70	—	—	0,3	0,007	0,007	—
2	1	0,05	1	100—150	—	0,1	0,2	0,03	0,007	—
3	0,2	—	0,3	70	—	—	0,1	0,02	Traces	—
4	0,07	—	0,01	—	—	—	0,03	—	0,01	—
5	0,01	—	—	—	—	—	—	Traces	0,02	—
6	0,05	—	0,03	30	—	0,1	0,1	—	Traces	—
7	0,1	—	0,1	70	—	<0,1	0,1	—	—	—
8	0,07	—	0,1	70	—	0,5	0,1	0,007	—	—
9	0,2	—	0,01	—	—	—	0,05	—	—	—
10	0,7	—	1	80	—	—	0,07	0,1	—	—
11	0,1	—	0,03	—	—	—	0,06	—	—	—
12	0,5	0,2	≥1	100	—	<0,1	0,2	—	—	—
13	1	<0,1	0,03	1000	0,3	<0,1	0,01	—	Traces	—
14	>1	0,1	≥1	300	0,5	0,1	0,1	—	—	—
Pyrite veins in polymetallic ore fragment										
1	1	0,1	—	1000	0,3	1	0,3	—	0,007	0,1
2	0,3	—	≥1	150	—	0,3	0,3	—	—	>1

Note. Ag content given in g/ton; other elements, in percentages. Analyses by N. G. Korennovaya.

Pyrite and sphalerite crystalloclasts occur in all varieties of detrital ores. They are most abundant in layered ores where they represent practically the entire detrital ore body. Pyrite crystalloclasts are grains of 1-2-mm diameter, with well defined cubic and pentadodecahedral habit in which etching reveals growth bands. Their orientation coincides with crystallographic boundaries. Most grains are not rounded or truncated and resemble metacrystals more than fragments. Only on rare occasions are growth zones truncated by outside grain boundaries, indicating that the truncation of crystalloclasts probably occurred during transport (Fig. 5a).

Sphalerite crystalloclasts are of 2-3 mm size, isometric; rarely sphalerite concretions. Their zonal structure is identical to that of sphalerite in polymetallic ore fragments. Galena inclusions also occurs. In this instance, zones are often truncated by crystalloclast boundaries.

They may be represented by framboids and framboid groups, coarse-grained earthy masses, aggregates of very small concentric, zonal spheroids, with rhythmic sphaeroids. Not only pyrite; galena, sphalerite, chalcopyrite, quartz, and finely dispersed vein matter with radiating structures (Fig. 5e) may also be included, along with pseudomorphs after organic residue (Fig. 5d). In addition to the noted zonal growth bands with pyrite, sphalerite, chalcopyrite, and galena fill interstices between vein minerals.

Metacolloidal pyrite also occurs in aleurolitic layers among layered fine detrital ores where chains of small framboids are stretched out parallel with the bedding plain.

Indication of bottom-dwelling organism in certain layered ore samples appear as paired parallel bands composed of organic matter. They may represent worm burrows walls. Numerous marcasite pseudomorphs developed after unidentified organic residue, possibly fish bones (Fig. 5d). Minerals in the cement have distinctly corroded both the fine and the coarse ore clasts and healed their internal fractures (Fig. 5e). As the result, the surfaces of certain fragments obtained serrated shapes. Pyrite crystalloclasts often are overgrown by a thin marcasite rim, of comb-shaped configuration (Fig. 5e, f). Growth rims, composed of alternating quartz and marcasite bands, occur occasionally.

In the detrital ores indications of oriented pressure are locally expressed by subdued schist development from silty-pelitic matter and development of so-called pressure shadows near certain pyrite-, rarely sphalerite, crystalloclasts. These form fibrous quartz rims around fragments and parallel with schistosity. During etching, fibrous pressure twin develop in sphalerite fragments.

Zonal pyrite crystalloclasts, present in all detrital ores, may be regarded as metacrystals, due almost completely to the absence of rounding and truncation features. A comparative study of geochemical characteristics of these and meta-colloidal pyrites has been undertaken in the detrital rock cement, with laser electron microprobe LMA-10. Results (Table 1) indicated that pyrite in the cement differs from pyrite crystalloclasts, enriched in Cu, As, Ag, and Mn and typical of late pyrite generations in most pyrite deposits. Pyrites from carbonate-pyrite veins were analyzed. The veins intersect fragments of brecciated, essentially sphaleritic polymetallic ores. Geochemically, they are close to metacolloidal pyrites that occur in the cement of detrital ore and differ only in the presence of Ba and higher Ag concentration.

The data indicated that all massive ore varieties with associated compositional, structural characteristics, and the mineralized chloritoliths occur in ore clasts in the detrital ores. Massive ores and the underlying chloritoliths, and the enclosing rocks probably formed in adjacent areas. Subsequent hydrothermal activity probably did also occur after the basalt lava erupted and covered the ore horizon [11].

* * *

(1) Massive sulfide ores of the Korbalkhinsk deposit accumulated at the toe of an underwater volcano on a dissected surface that resulted in variable facies conditions of the ore-bearing volcanogenic-sedimentary rocks.

(2) A canyon that extended southeastward from the massive ores of the Korbalkhinsk deposits was an essential paleorelief element.

(3) Seismic activity and underwater weathering caused partial disintegration of the massive ores. The detrital ore matter concentrated in the canyon channel. Ore breccias of landslide origin gradually alternate with proximal ore turbidites, with increasing amounts of admixed nonore detrital matter as the function of the distance from the source area.

(4) Similarity of sedimentary structures, character of sedimentary components, and characteristics of lateral distribution of rock varieties with similar granulometry, point to the uniformity of formation conditions.

(5) The presence in the detrital ores of practically all massive ore varieties and subore chloritoliths indicates the almost synchronous deposition of massive ores and the enclosing rocks.

(6) Decomposition and erosion of massive ore deposits were associated with continued hydrothermal activity, suggested by hydrothermal cementation of ore fragments and slump breccias near the massive ore deposits.

This project was undertaken with the support of the Committee of the Russian Federation for Geology and Mineral Resources (ROSKOMNEDRA).

LITERATURE CITED

1. I. V. Gas'kov F. G. Distanov, N. Yu. Mironova, et al., Upper Devonian Polymetallic Pyrite Deposits, Northwestern Altai Ore Range [in Russian], Nauka, Novosibirsk (1991).
2. I. V. Gas'kov and N. Yu. Mironova, "Genetic model of Upper Devonian polymetallic pyrite deposits of the northwest Altai Ore Mountains," in: Ore Genesis and Genetic Model of Endogenic Ore Formations [in Russian], Nauka, Novosibirsk (1988), pp. 98-107.
3. V. P. Dmitriev, "Geologic makeup and areal distribution of ores, Korbalkhinsk Deposit," Vestnik, State University of West Siberia and Novosibirsk, No. 2, 45-58 (1963).
4. A. G. Zlotnik-Khotkevich, "Diagenetic alteration of pyrite ores," Geologiya Rudn. Mestorozhdenii, No. 2, 83-98 (1992).
5. I. V. Kreiter, V. V. Kuznetsov, I. P. Pugacheva, et al., "Geology and formation conditions of the Korbalkhinsk polymetallic deposits of the Altai Ore Range," Geologiya Rudn. Mestorozhdenii, No. 5, 37-40 (1982).
6. S. Carey and H. Sigurdsson "Volcanic sedimentary model in marginal basins," in: Geology of Marginal Basins [Russian translation], B. P. Kokelaar and M. F. Howells, Mir, Moscow (1987), pp. 52-64.
7. E. F. Maleev, Handbook of Volcanic Rocks [in Russian], Nedra, Moscow (1980).

DISCOVERY OF GOLD DEPOSITS IN ANCIENT CONGLOMERATES IN RUSSIA

A. A. Konstantinovskii

UDC 553.411.072 (470.3)

Precambrian and Paleozoic auriferous conglomerates in various areas of the East European and Siberian Platforms and their folded framework have been investigated. Geological conditions of the distribution pattern, types of ore-bearing terrigenous formations; structure, composition of ore-bearing beds and auriferous conglomerates of known foreign deposits are similar. This points to settings, favorable for gold concentration in conglomerates of the study area. The formulated general concepts aided in analyzing extensive areas and recognizing local gold prospects in them. Distinct stratigraphic and lithologic controls, indicative of primary placer genesis govern gold mineralization. As in foreign deposits, gold remobilization and redistribution did take place, especially locally.

Globally, the largest gold deposits are associated with ancient conglomerates. Gold often occurs with U, Ir, Os, rare metals, Ag (as Au-admixture), and diamonds. High Au-content, the complex ore configuration and numerous unsolved genetic questions about the deposits explain the continued interest in the origins of and exploration for auriferous conglomerates. The South African Witwatersrand deposit is the largest of these. It yielded 40,000 tons of gold in the past century, globally about one-third of all gold ever mined. Highly valued associated components are also mined alongside gold [3] (Table 1).

In addition to South Africa, gold-bearing conglomerates have been mined at different times in Ghana (Tarkwa ore belt), Brazil (Jakobina ore field), Australia (Nallagain ore zone), and the USA (Lead Field, Black Hills of South Dakota), [13, 19-21, 23, 24, 26, 28, 29, 33, 39, 40]. However, the productivity of the other regions does not equal that of unique Witwatersrand, with its six U—Au fields and 122 ore mines and deposits [1, 6, 13, 19, 31, 34-38, 42]. This rare deposit type is the object of the present study. Conglomerates of the same mineralogy, but of low Au content occur in most Prebaikal platform areas and rim zones [1, 3, 8, 18-20, 41, etc.].

A summary of information on foreign deposits yield the following essential conclusions:

(1) Commercial gold conglomerates are mostly Precambrian (2.3-2.7 Ga age). They are associated with the sediment blanket that covers stable crustal blocks (cratons and protoplatforms); to a lesser extent, with mobile marginal zones. During the formation process, gold originated from Archean, in part early Proterozoic granites-greenstones, also from carboniferous terrigenous shales with disseminated gold minerals. No major deposits occurred, but a large number of shows and small deposits.

(2) Gold mineralization is strongly controlled by stratigraphy, lithology, to lesser extent, by structural properties. Ore-bearing conglomerate formation are associated with basal beds; less frequently, the top interval of the of tectonic-sedimentary cycles. They occur along the fringe of the sedimentary basin, especially along steep rim escarpments, associated with stepwise downthrow or flexures. They are distinguished by highly mature, quartzitic composition. Gold conglomerates in the paleobasin margins are associated with specific terrigenous facies; alluvial fans or downthrown basement blocks, stable coastal zones, and deepened valley sectors near valley mouths. Mineralized "reefs" are thin (c. 15-25 m) and composed of interlayered fine- and medium quartz- and siliceous quartz conglomerates, puddingstones, cross-stratified quartz sandstones and gritstones. In reefs of commercial gold concentrations (5-10 g/ton, and greater) only individual thin (0.05-0.5 m) layers ("bankets" and "rudites") of well sorted conglomerates occur with indications of repeated reworking. Reefs include thicker quartz sandstone beds, occasionally with shales. In rudites, gold occurs in the cement and is associated with lower bed intervals, with clastic heavy mineral clastic minerals, to frontal laminae of cross-stratified sets in puddingstones and gritstones.

(3) Gold particles in conglomerates usually are very small (0.01-0.1 mm), of high speck (gold particle) count (900-1000) and mostly recrystallized. Gold often forms pseudomorphs after associated minerals, cover them with a gold film or forms "gaps" at the cement—gravel boundary. However, small numbers of gold particles always occur even in

lower Precambrian metamorphosed conglomerates. They bear indications of primary placer genesis, including roll bodies of quartz, zircon, chlorite, and other clastic minerals in the conglomerate rims [1, 4, 19, 30, 35, 36, 43]. The background concentration range of the metal in gold fields excluding rudites, was 0.1-0.9 g/ton.

(4) Gold-bearing bodies that cut through gold reefs are rare. Their productivity is much lower than that of stratiform deposits. They often occur in zones where conglomerate-bearing formations have undergone intermediate-level zonal metamorphism and, in particular, local granitization (e.g., Sierra Blanco, Morro-de-Venta, Joao Belo in Jakobina Field).

Conglomerate-related gold deposits have not yet been discovered in the territory of the former USSR. Only individual shows, without commercial importance occur. Primarily due to the absence of commercial gold conglomerates despite these discoveries, geologists in this country discounted the possibility of commercial discoveries. It was assumed that such conglomerate are very rare or unique. Forecast and exploration activities in the territory of the former USSR, including Russia, have been insufficient in this respect.

However, the negative attitude is hardly justified. General summaries and comparison of data between Russian and foreign commercial deposits established that these deposits are rare not so much because of peculiar characteristics but because of the scarcity of information on the conglomerates. Continued exploration is encouraged by the presence of numerous gold shows. Often these occur in combination with diamonds, rare metals, Ti-bearing minerals and other valuable components in Precambrian and Paleozoic conglomerates in the former USSR, in particular, Russia. Exploration problems of gold conglomerates in this country have been under study at different times by G. P. Volarovich, V. S. Voitovich, L. M. Ganzha, P. K. Dement'ev, Yu. N. Deryugin, A. M. Druzhinin, A. P. D'yachenko, T. P. Zhadnova, O. N. Zakharova, D. K. Zegebart, Yu. P. Ivensen, N. D. Kononov, V. N. Kotlyar, B. L. Koshelev, F. P. Krendelev, V. A. Kudravtsev, V. I. Levin, T. V. Meshcherina, I. V. Mikhailov, A. P. Mordvin, V. Z. Negrutsa, V. S. Ozerov, G. V. Pisemskii, I. S. Rozhkov, V. A. Savel'ev, Yu. I. Simonov, A. V. Sinitsyn, V. V. Ushkov, G. Kh. Fainstein, A. E. Tsaplin, V. M. Chaika, B. R. Shpunt, L. A. Yachevskii, the present author, and others.

As the result of these investigations, gold shows had been located in lower Proterozoic, Riphean, Vendian and Paleozoic conglomerates of numerous areas. (Mesozoic and Tertiary conglomerates and gravel deposits would not be discussed presently.) Most of these areas resemble settings of commercial deposits abroad. Based on already established gold resources, hope exists for future exploitation.

CHARACTERISTICS OF GOLD-BEARING AREAS

The KMA Block, Voronezh Massif. In tectonic terms, this region represents a typical Archean granite-greenstone craton, subdivided into three early Proterozoic synclinorium belts, and covered by 70-250 m blanket of Paleozoic and Mesozoic deposits. The gold-bearing conglomerates occur in the basal terrigenous beds (Stoilensk Formation). This is a thick (5-7 km) iron ore and schist-bearing miogeosynclinal complex that developed in the discussed zones. The zones continue northwestward to a significant distance (Fig. 1). According to drill and geophysical data, the Krupetsk-Ryl'sk Zone extends for a 170 km distance, the Belgorod-Mikhailovsk Zone, for 350 km, the Alekseevsk-Voronezh Zone for 385 km. Each zone is 6-50 km wide. The limbs are steeply inclined, overturned. A potential auriferous unit, the Stoilensk Formation at the base of the section represents a lower Proterozoic complex. It was dated indirectly as 2.6 Ga. This formation developed as a blanket deposit in all three zones, overlying the Archean basement (the gold source) and a weathering horizon, with angular unconformity. As in the rim zone of the Witwatersrand Basin, these have been essentially associated with the greenstone zone; less often with the intersecting granitoids. Gold occurs in the sulfide quartz mineralization zones, in komatiites, metabasites, granites, and quartz veins [2, 7, 14, 18].

The Stoilensk Formation consists of light gray quartzites and quartzitic sandstones in the upper section, interlayered with micaceous shales with garnet, staurolite, and sillimanite. They are 40-1500 m thick. The conglomerates consist of numerous lenticular layers in the lower part of the section. The pebbles are small-to-medium, almost exclusively quartzitic. Quartz, sericite, fuchsite, rarely chlorite, pyrophyllite, and chloritoid occurs in the cement. The basal, conglomerate-bearing interval is altered in proportion to changes in the total thickness of the formation. It thickened to 550 m above the intercupola greenstone depression of the basement. The thickened lenses are 10-20 km wide (Fig. 2). Individual areas with sharply increased thickness of the basal unit (Fig. 1) displayed dominant fluvial, mostly alluvial fan facies of polycyclic composition. The local syndepositional basin regimes and the facies types indicate the great similarity between the investi-

gated areas and the gold fields of Witwatersrand. However, differences also exist; the fan sequences are transgressive, not regressive as in Witwatersrand. Regressive conditions favor accumulation of large amounts of primary sedimentary-, to a large degree, placer gold [19]. This circumstance reduces gold prospects for KMA conglomerates. According to our analysis of small and medium-scale geological maps of the basement, a number of such, potentially gold-bearing areas have been provisionally identified in the synclinorium zones. The basal Stoilensk Formation interval abruptly thins over the granite-gneiss complex, wedging out in areas where block-cupola structures subdivide its distribution area near the uplift. In contrast with the buried sequences, sandy-gravel beach deposits dominate. Judging from the known ore deposits, these units hold less promise.

The conglomerate composition also indicates great similarity with U-Au reefs of Witwatersrand of the same age. These units and others belong to the older, rare sulfide-uranium ore facies.* This indicates, first, the abundance of small, isometric, in part rounded pyrite and pyrrhotite grains in the cement that impact the appearance of the rock structure (Fig. 3) and are totally uninfluenced by cleavage fractures. Second, the increased radioactivity of the conglomerate beds was due to small (0.05-0.07 mm) uranium crystal grains in the cement [18]. In addition to the dominant sulfides, as the Witwatersrand reefs they also contain high concentrations (locally, maximum 65 kg/ton) of zircon, leucoxene, and chromite (data by L. M. Ganzhi).

The gold content of the conglomerates has been but poorly and erratically studied. Only individual local areas were tested. It was established for the first time that the gold content in most samples is two magnitude order higher than the Clarke concentration in detrital rocks. It is several tenths of grams per ton. Identical background concentrations were found in ore reefs of the Witwatersrand, Jakobina and Tarkwa. As earlier indicated, this was done without calculating commercial gold rudites. Against this background, only a few samples with high gold concentration were taken in studied areas of the KMA. Concentration values of these samples were similar or identical to those obtained from foreign gold rudites. High values occurred sporadically and outside of local ore zones. They came from drillholes, drilled for different reasons. These values thus represent chance occurrences [2, 7, and 18]. Gold occurred at the base of some of the auriferous beds (data by G. V. Pisemskaya). The metal was powdery, visually undistinguishable from the nonore portion, and provided a significant (93+) particle count. Only a small portion of gold was associated with pyrite (maximum 3.3 g/ton), pyrrhotite (maximum 11.0 g/ton), and micas in conglomerates (maximum 6.0 g/ton).

The *Karelian Massif* represents an Archean granite-greenstone structure in the Baltic Shield. It differs from the KMA area by the different age relationships of the greenstone and granite-gneiss complexes. In the KMA area the granite-greenstone complex is older. Also, the Proterozoic beds are associated with a very thick (3-5 km) protoplatform cover. It was deformed in northwest-oriented, broad folds and cut by longitudinal faults. Gold conglomerates occur at the base and middle portion. The conglomerates are related to two ore-bearing formations.

The older ores (2.5-2.7 Ga) includes radioactive pyrite-bearing oligomict conglomerates, similar to those of the KMA area. They formed at the base and middle interval of the Sumi terrigenous-volcanic complex, basal member of the protoplatform cover sequence. It is of similar age and position as the basal unit of Dominion Reef Supergroup of Witwatersrand. Conglomerates of this type occur in the basal Okunevsk (150-250 m) and the higher Zheleznovorotinsk Formations (maximum 220 m thick), in limbs of the Shombozersk and Lekhtinsk graben-syncline structures, and in the northern Karelian Massif. A. I. Leont'ev, V. V. Ushakov, et al. discovered numerous gold occurrences of c. 1 g/ton gold concentration. In a detailed study of one of these, A. M. Druzhinin indicated presence of a sizable gold concentrate at the base of the conglomerate sequence.

The younger magnetite-martite formation, alternating with a sulfide-uranium mineralization, include conglomerates, deposited at the base of the Jatulian complex of c. 2.3 Ga age. The thick volcanic-sedimentary sequence of complex composition, is characterized by high detrital content. It is unconformably overlain by Sumi beds and overlying volcanites, schists and the Saroli boulder conglomerates [3, 15, 25]. In the limb areas of the structure it is transitional toward the

*Four categories have been identified among the conglomerate-bearing Russian ore formations on the basis of associated heavy minerals and rock parageneses: sulfide-uranium, magnetite-martite, hematite, and low-iron ores. From the early Precambrian on, with its low-oxygen atmosphere [6, 8, 20, 27], to the later Precambrian with an increased role of oxide mineral association, these types grade into and alternate with each other. This fact accounts for the diminished gold content in conglomerates [8 and 22].

TABLE 1. Value of Minerals Produced in Witwatersrand [36]*

Product	Value million dollars	Percent
Gold	31,557,492	92.98
Uranium	2,183,777	6.43
Silver**	109,856	0.32
Pyrite***	79,147	0.23
Platinum-group metals	11,402	0.03
Diamonds	0.019	0.01
Total	33,941,695	100.00

*Quantitative ratios did not vary significantly up to the present.

**Pyrite mixed in gold ore.

***Pyrite utilized in sulfuric acid production.

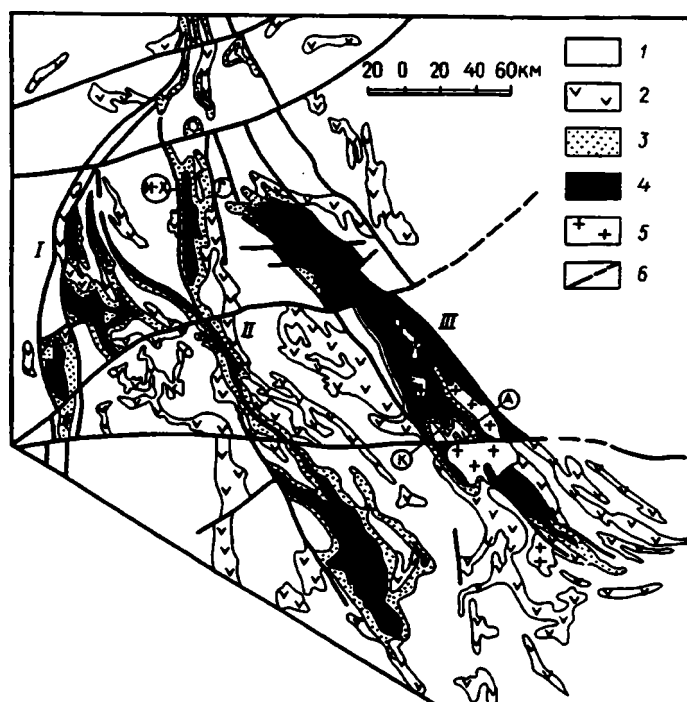


Fig. 1. Distribution of early Proterozoic synclinoria in the KMA region (based on a simplified summary by Tsentregeologiya). 1-2 – Archean granite-greenstone basement (1 – granite-gneisses; 2 – greenstone field, with gold mineralization); 3-4 – Lower residual concentrations of placer gold. Gravels and pebbles, carried by paleocurrents formed gold placers beyond the ledges. Gold concentration quickly diminished in them and their marginal zone (Fig. 6, upper cross section, left margin).

Archean basement. The Jatulian conglomerates contain abundant concentrates (maximum 140 kg/ton) clastic magnetite and martite among the heavy minerals. Often, they form natural, black ore concentrate layers and trains of coarse gravels that indicate paleocurrent directions. Prospects of gold-bearing conglomerates have not yet been established as well as those of the sulfide–uranium ore type. Only one such deposit, Kaarestunturi [32], is presently known. It is still being explored. That deposit occurs in northern Finland, in the Yangozer, Lekhtin, and Shombozer structures of Karelia. Gold-quartz conglomerates of the deposits form part of the Jatulian complex and locally, near the bottom of the beds contain maximum 20 g/ton gold. As in Karelia, the rocks are impregnated by martite and magnetite.

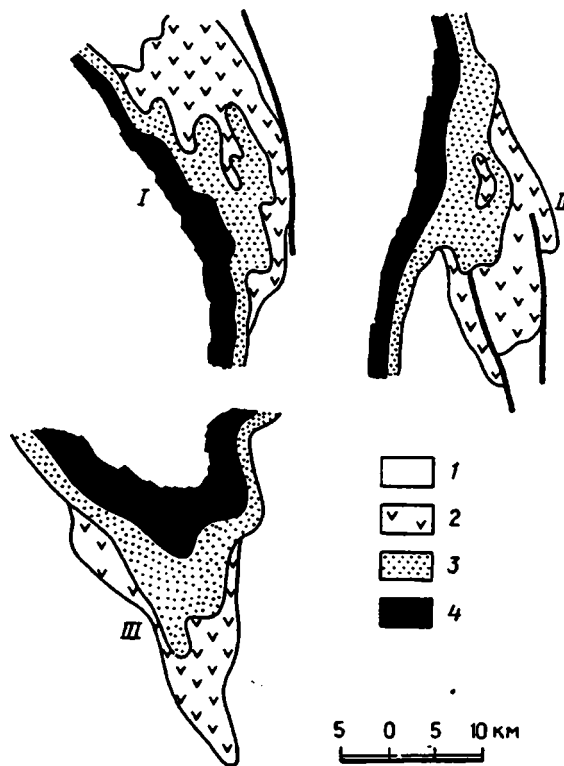


Fig. 2. Typical bulges of thickened Stoilensk Fm interval, with basal conglomerates, located above buried Archean basement blocks in present structure. 1-2 - Archean basement (1 - granite-gneisses, 2 - greenstone complex); 3-4 - Lower Proterozoic protomiogeosyncline complex (3 - Stoilensk Fm. with gold-bearing conglomerates in basal interval, 4 - iron quartzites of Korobkovsk Fm); I-III - potential gold ore zones, differing in details of the present structure (I-II - on east limb of Mikhailovsk Synclinorium; III - on south closure of Belgorod Synclinorium, Belgorod-Mikhailovsk Synclinorium belt).

Conglomerates with gold shows are associated with the 100-450 m thick Maimyarvi Formation and the overlying Yangozersk (200-640 m) Formation, at the base of the Jatulian complex. They occur at the same stratigraphic level as the auriferous Kaarestunturi conglomerates. Both formations resemble the basal interval of the Stoilensk Formation in the KMA area. Their thickness varies greatly along the limbs of the structure and form thicker intervals over the buried, essentially greenstone, blocks of the Archean basement. In these areas alluvial-colluvial fan deposits dominate (Fig. 4) in broad separated zones; thinner deposits of nearshore alluvial plains and pebbly marine beaches also occur.

Elongated-braided gold distribution patterns are typical in bank-parallel bars. These usually stretch from fan margins toward the southeasterly. The largest bars reach 3 km length, 0.6 km width, and consist of a 6-m-thick gravelly, sandy-pebbly lithosome. Bar facies, in ancient alluvial fans [36, 42] contained the highest gold content in conglomerates of the Witwatersrand deposits.

In the alluvial fans and bars in the investigated local basin and in basal horizons of the sediment blanket over the Central Timan area gold particle size generally is very small (0.1-0.25 mm). The particles are well-sorted and carry traces of rounding. Count values are high (960-999). One of their dominant characteristics, according to L. A. Nikolaeva, is a deeply intruding, recurrent, restorative corrosion, caused by weathering horizon processes, recrystallization of the surface layer, and plastic deformation. These features indicate the presence of gold in pre-Yaransk paleo-placers [10].

The uneven gold distribution in the producing horizon of the Yaransk Formation within a locally enriched basin and the small size of individual gold-enriched bodies explain the sharply reduced gold concentration values that contrast

TABLE 2. Characteristics of Precambrian and Paleozoic Gold-bearing Conglomerates in the Ural and Siberia

Region	Paleotectonic position	Geological age	Main source types of gold ore formations and enclosing complexes	Type of conglomerate and gold-bearing formations	Gold-bearing terrigenous facies	Characteristics of gold-bearing conglomerates	Concentration of heavy clastic minerals	Associated placer minerals	Locally gold-enriched conglomerate bodies		Gold distribution in conglomerate horizons
									number of samples (in %) with 0.1-1.0 g/ton	individual ("marker") samples with increased (+) and high (++) content	
Kozhinsk Uplift (polar Ural region)	Paleozoic miogeosyncline	Upper Cambrian – Lower ordovician	Ag-Sulfide-quartzitic	Low iron content	Alluvial fans, mouth-sectors of paleovalleys, nearshore marine (pebble beach)	Oligomict, medium-coarse pebbly, locally with boulders, various stages of rounding, thick lenses and beds	Locally high (maximum 3-5 kg/ton)	Platinum group minerals (individual grains), xenotime, zircon	35-45	++	With indications of reworking, appearance of intersecting mineralized zones and quartz veins with gold
Yenisei Ridge	Riphean miogeosyncline	Upper Riphean	Gold-sulfide-quartz-bearing, low-sulfide and carbonaceous schists of the Early Baikal basement	"	Nearshore marine (pebble beaches)	"Schist-bearing" pebbles composed of quartz and schist – thin layers	Moderate	Ilmenite, leucoxene	40-45	++	Same
Sayan Uplift (Khuzhir area)	Pericratonic depression	Lower Vendian	Gold-sulfide-quartz assemblage in carboniferous shales, ultramafites (?) and gneisses(?) of the early Precambrian basement	"	Alluvial fans, probably reworked by the post-Vendian sea	Polymict (30% quartz content in the pebbles), fine and medium pebbly, lenticular beds	Very high (maximum 50 kg/ton)	Zircon, rutile, ilmenite, leucoxene (weight composition), monacite, cassiterite, probably diamond	40-45	++	Layered, braided, with nests
Aldan Shield (west slope)	Proto-platform (cover)	Lower part of Lower Proterozoic	?	Magnetite-martite	Nearshore marine, fluvial (colluvial?) fans of continental piedmont area	Oligomict and quartzitic, fine-to-medium sized pebbles, thin layers, polymict boulders, thick lenses	Locally very high (maximum 25 kg/ton), due to presence of magnetite	Zircon, monacite	15-20	+	With indications of reworking, appearance of intersecting mineralized zones and quartz veins with gold
Aldan Shield (east slope)	Protoorogen basins (paleo-rifts)	Upper Lower Proterozoic	?	Hematite-bearing	Same	Same	Very high (maximum 30-40 kg/ton), due to presence of hematite	Zircon, ilmenite, leucoxene, monacite, xenotime	8-10	+	Same

TABLE 2 (continued)

Region	Paleo- tectonic position	Geolog- ical age	Main source types of gold ore formations and enclosing complexes	Type of conglom- erate- and gold- bearing forma- tions	Gold-bearing terrigenous facies	Characteristics of gold-bearing conglomerates	Concentration of heavy clastic minerals	Associated placer minerals	Locally gold-enriched conglomerate bodies		Gold distribution in conglomer- ate horizons
									number of samples (in %) with 0.1-1.0 g/ton	individual ("marker") samples with increased (+) and high (++) content	
Olensk Uplift, Siberian Platform	Recent proto- platform (quasi- plat- form)	Lower Riphean Lower Vendian, Permian	Gold-sulfide-quartz, in carbon-enriched phyllites, greenschists, and granites of the early Precambrian basement	Low iron content	Nearshore marine, colluvial piedmont fans, deepened-paleo- valley	Quartz and subarkosic, from fine to coarse pebbly. Exposed layers. Quartzitic conglomerate-breccias. Polymict, lenticular beds	Locally high (maximum 5.7 kg/ton)	Ta-Nb (weight comp.), zircon, ilmenite, rutile, diamond	30-40	+	Layering; in Permian deposits: nests and braiding
Gornostakhsk Anticline (east rim of Siberian Platform)	Riphean miogeo- syncline	Lower Middle Vendian	Gold-sulfide-quartz- bearing, low-sulfide and carbonaceous schists of the Early Baikal basement	"	Nearshore marine (pebble beaches)	Siliceous-quartzitic fine-to-medium pebbly. Thin exposed layers	?	?	30-40	+	Layered, locally with intersecting ore-bearing beds and quartz veins with gold
Tonodsk Anticlin- orium (Patomsk Upland)	Recent protoplatf- orm (quasi- plat- form)	Upper Lower Protero- zoic	Oligomict, medium-coarse pebbly, locally with boulders, various stages of rounding, thick lenses and beds Bilyakchansk Uplift (eastern rim of Siberian Platform) Proto-orogen basins (paleorifts)	Hema- tite- bearing	Alluvial fans, reworked by marine processes; nearshore marine (pebble beaches)	Quartzitic, fine-to-medium sized pebbles, thin layers and lenticular beds	Locally high (maximum 15 kg/ton), due to presence of hematite	Ta-Nb (weight comp.), zircon, rutile, ilmenite, leucoxene	45-50	++	Layered, locally with certain amount of gold reworked in intersecting zones
Bilyakchansk Uplift (eastern rim of Siberian Platform)	Recent proto- platform (quasi- platform)	Same	?	"	Colluvial alluvial fans, continental piedmont facies, nearshore marine (pebbles beaches)	Polymict boulders, thick lenses; oligomict, medium pebbly. Thin layers exposed	Locally very high (maximum 120 kg/ton), due to presence of hematite	Zircon, rutile, ilmenite, leucoxene, thorite, orangite (weight composition)	?	+	Layered
Northeast Taimyr	"	"	"Schist-bearing"- pebbles composed of quartz and schist- thin layers	"	Alluvial and colluvial fans, nearshore marine	Fine-grained detrital quartz conglomerate-breccias and small pebbly oligomict conglomerates. Corresponding thick lenses and layers	?	Zircon, rutile, ilmenite, leucoxene	?	+	Layering, locally with indications of reworking and insignificant redistribution of matter

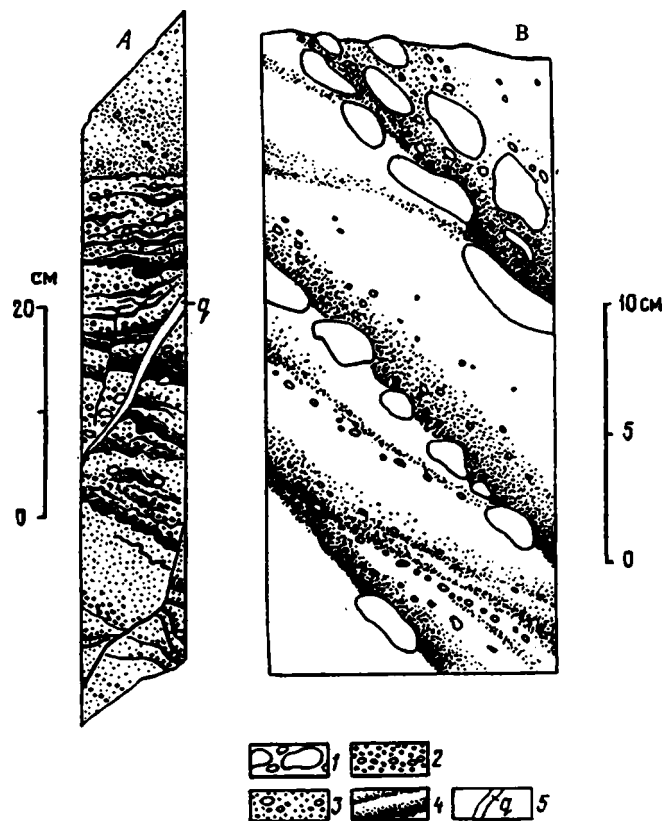


Fig. 3. Cross-stratified puddingstone-conglomerate in basal Stoilensk Fm. interval, with laminae of fine-grained pyrite and pyrrhotite concentrate. 1 – Layers of fine- and medium-sized quartz pebbles in puddingstones; 2 – quartz-gritstone with fuchsite and dispersed blue and blue-gray quartz grains; 3 – cross-stratified puddingstone; 4 – layers of fine, rounded pyrite and pyrrhotite grains (natural alluvial sand concentrates); 5 – intersecting quartz veins with low gold content; A, B – core intervals from Korobkovsk and Aleksandrovsk areas (Belgorod Expedition Core Depository).

with data from drill cores. Gold-rich ore bodies are rarely encountered even by closely-spaced sets of drillholes. Comparison of open pit mine Proterozoic protomiogeosyncline complex (3 – Stoilensk Fm, enclosing conglomerates with gold shows, 4 – iron-bearing quartzites, carbonaceous phyllites, mica schists, marbles, metasandstones); 5 – early Proterozoic intrusives; 6 – proven (solid lines) and assumed (dashed) faults; I-III – synclinorium zones (I – Krupetsk-Ryl'sk; II – Belgorod-Mikhailovsk; III – Alekseevsk-Voronetsk Zones). Individual study area with thickened basal conglomerate units in Stoilensk Fm: K – Korobkovsk; A – Aleksandrovsk; G – Gremyachinsk; I-K – contiguous Ignateevsk-Khal'zevsk area.

The basal Maimyarvi Formation is underlain by the subbasal, fragmented Eningivaari Formation. It consists of arkosic, rarely quartzitic meta-sandstones and puddingstones that fill paleo-valleys, cut 150 m deep into rocks of the substrate. The substrate consists of crystalline basement rocks, covered by the Sumi and Sarioli Formations. In contrast with the Maimyarvi and Yangozersk Formation, this formation was untested for gold content.

The gold content of magnetite-martitic conglomerates has been better studied than those of the sulfide-uranium ores, but still unsatisfactorily in assessing their prospects. At various types V. Z. Negrutsa and V. V. Ushkov and other workers discovered a great number of gold shows in the Koikar, Lekhtinsk, Shombozersk, and in particular, the Yangozersk structures [3, 15, 25]. The gold concentrations in most shows are in the range of hundredths-to-tenths of g/ton. However, in certain areas, studied in detail, high gold concentrations have also been encountered. This occurred in the alluvial-colluvial fan deposits on the east limb of the Yangozersk structure (Fig. 4), less frequently in beach gravel deposits (Koikar structure).

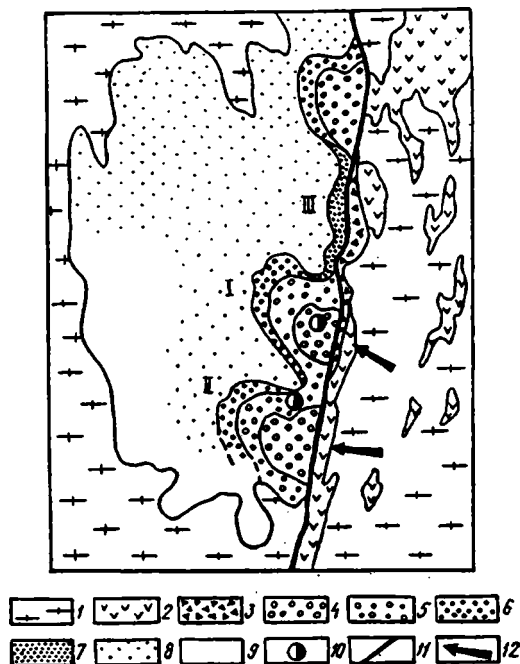


Fig. 4. Lithofacies map; basal units of Maimyarvi Fm. (Lower Jatulian complex), east limb of Yangozersk Structure, Karelian Massif. 1-2 - Archean basements; 1 - granite-gneisses; 2 - Loppi greenstone complex with shows of gold mineralization in metabasites of iron quartzites; 3 - coarse-detrital conglomerate breccias and phyllites, Sarioli Complex; 4-8 - basal conglomerate-bearing interval, Maimyarvi Fm. (4 - boulder-conglomerate from proximal (headward) zone of alluvial fans; 5 - coarse pebbly conglomerates of middle alluvial fan sectors; 6 - medium- and fine-grained conglomerates and gritstones of the peripheral-distal zones of alluvial fans, most favoring gold accumulation; 7 - conglomerates and gritstones of ancient beaches; 8 - shallow water sand facies; 9 - basalt unit of Maimyarvi Fm, not drilled; 10 - high levels of gold concentration in conglomerates; 11 - syndepositional paleo-fault zone; 12 - transport direction of detrital gold-bearing sediments; I-III - potential areas for future mining operations (I - Maimyarvi; II - Sovdozero; III - Énningilampi).

Gold in most shows had powdery consistency and high particle count. It concentrated at the base of the beds, primarily in surface depressions, overlain by the conglomerates. As shown by the Yangozersk structure on a larger scale, its distribution was regulated by alluvial fan and pebble beach facies. As in the KMA area, this indicates the primary nature of placer genesis. However, indications of gold remobilization and partial redeposition did occur locally where rock alteration involved chlorite, magnetite crystal formation, and other mineralization,

As V. Z. Negruța and V. V. Ushkov have established, gold particles have grown to reach 1-1.5-mm diameter or assembled into 2-3-mm clusters, similar to those in Witwatersrand reefs [36]. Gold film enveloped the associated minerals. Gold emulsions also developed in chlorite of the conglomerate and puddingstone cement. Gold grain count values were high (984-998). The total gold content increased significantly (e.g., Gold Show Yatulia-1).

Gold-sulfide-quartz mineral zones in metabasites of Archean greenstone basins represented the dominant gold source of sulfide-U conglomerates in associated gabbroid massifs and iron quartz horizons, especially in the so-called sulfide facies. Young gold ore shows in metavolcanites and carboniferous Sumi and Sarioli phyllites were additional gold sources of magnetite-martite conglomerates.

Central Timan. This uplift in the lower horizons of the platform cover unconformably overlies the Baikal folded basement in the northeast part of the Russian Platform. According the geologists of the Ukhtinsk Expedition of the TsNIGRI, it contains a small gold placer deposit with diamonds, rare metals, rare earth elements, and Ti-minerals [10-12, 17].

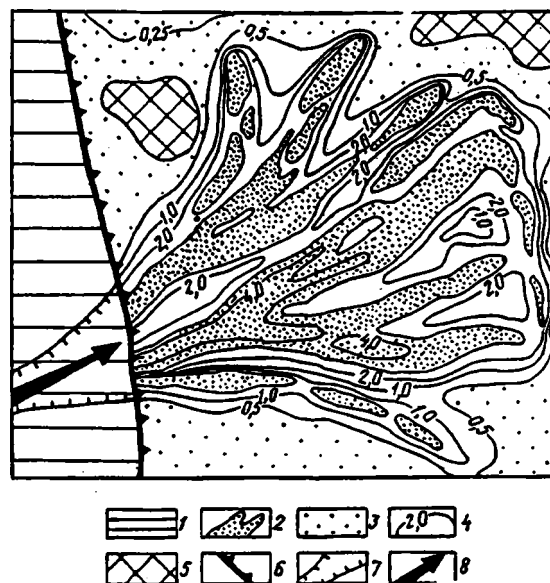


Fig. 5. Fan-shaped, braided gold distribution pattern in basal horizon of Yaransk Fm, southwestern part of local basin, near north margin of Vymsk Ridge, Central Timan area: 1) Baikal folded basement – paleo-uplift (after formation of the Yaransk Fm. covered by transgressive Upper Devonian deposits); 2) alluvial-colluvial fan deposits, reworked by Devonian sea. Alluvial fan in white, with braids, enriched in fine-grained gold placer deposits with diamond, rare-earth-, and precious metal minerals (dotted margin); 3) fine-detrital nearshore marine deposits of the basal horizons, Yaransk Fm.; 4) isopachs of producing basal horizon, Yaransk Fm., in m; 5) erosional areas and outcrops of deposits of the basal producing horizon; 6) paleo-sediment transport direction. From northwestern depositional basin, during Yaransk times; 7) assumed paleo-valley, cut into Devonian basin. Sediment transport route of gold and diamond-bearing matter; 8) paleocurrent direction in paleovalley.

The basic source of gold was in the local basement. This was a zone of vein-disseminated quartz-sulfide and sulfide mineralization in the carbon-phyllites and aleurolitic shales of Riphean and Vendian (?) age. Quartz veins and veinlets were also included. In the few studied locations the gold content was small. However, locally, as at northern Tsilemskogo Kamnya and the Vymsk Ridge, gold concentrates of a few g/ton did occur.

Placer gold was found in terrigenous beds of various ages in the lower parts of the platform cover. They contained practically no magnetite, martite and hematite as clastic minerals and are assigned to the "low-iron" ore category.

In small, mostly "index" concentrations, gold occurs in Lower Ordovician (?) red sands and sandstones that fill depressions of maximum 115 m depth and paleo-valley in the surface of the folded basement and enclose rich Ti-placers. This concentrations are typical of the covering Middle Devonian deposits that are continental sandy–clayey beds. They include maximum 40 m bauxite beds of the Zaoztrovsk Formation. Its lower, coarse-detrital horizons fill karst depressions. The higher, similarly Middle Devonian, Pizhensk Formation (maximum 415 m thick) typical shallow water-marine quartz sand formation gold is disseminated in the section of quartzitic gravels and puddingstones. Gold concentrations are expressed in hundredths, rarely, in tenths of g/ton. Only locally, in thin, discontinuous basal conglomerate beds does the concentration reach 1 g/ton. These low-Au deposits developed mostly in separate, grabenlike basement depressions, thinning, and gradually wedging out toward the intervening paleouplift zones.

The Yaransk Formation of upper Zhivetsk-lower Fransk age is the main auriferous formation. It developed in the same basins, but it is more widespread on the slopes of the ancient uplifts. It cuts through older deposits of the sediment blanket. Similarly with the Pizhensk Formation, the formation consists of yellowish-white quartz sands and weakly cemented sandstones with large-scale, deltaic and nearshore marine-type cross stratification (cross- and unidirectional,

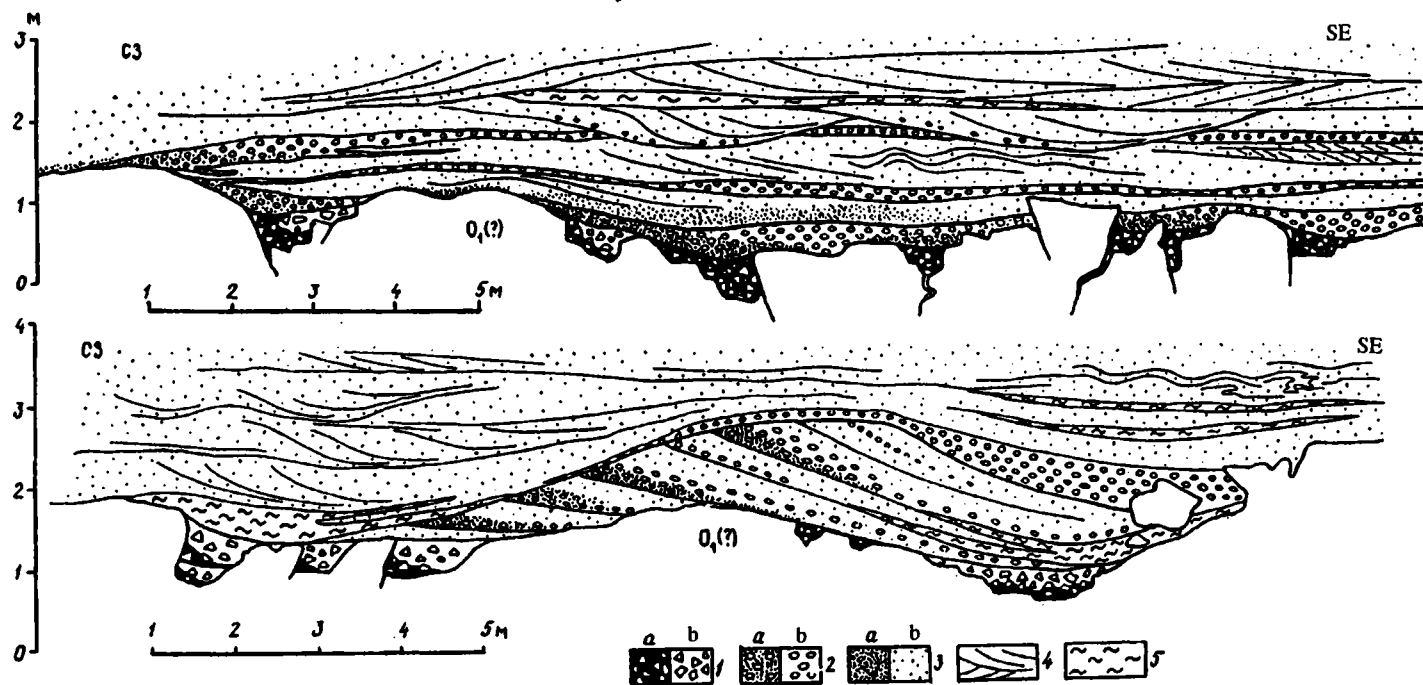


Fig. 6. Portions of section of producing basal horizon of Yaransk Fm within the central gold-bearing levels of the alluvial fan: 1) relict alluvial-colluvial fine-grained conglomerate-breccias and conglomerates with fragments and individual blocks of Lower Ordovician (?) red sandstones (a – gold-enriched, b – low gold content); 2 – fine and medium grained quartz conglomerates (a – rich; b – low gold content); 3 – sandstones and gritstones (a – gold-rich; b – poor in gold, or without gold content); 4 – cross-bedding; 5 – clays and argillites; O_1 – Lower Ordovician (?) red sandstones that underlie the Yaransk Fm.

diagonal stratification, locally convoluted). The total thickness of the formation reaches 35 m. In contrast with the Pizhensk Formation, a weakly cemented small-pebbly quartz conglomerate and gritstone horizon, locally transitional toward sedimentary rubble breccia, occurs almost always at its base. The lenticular beds are interlayered with cross-stratified puddingstones and sandstones, less often, with kaolinitic clays and argillites. Locally, the basal horizon is 0.2-9 m thick. Gold, diamonds, and other earlier discussed minerals are associated exclusively with this horizon.

Gold shows with measured weight values of that metal and the first known Russian paleoplacers with quartz conglomerates were discovered in the past years in a small (8×15 km) basin near the north end of the Vymsk Ridge, extension of the Baikal basement. Background concentrations of gold in basal horizons of the Yaramsk Formation in this basin were higher; in 48-55% of the core samples its content was 0.2-0.9 g/m³. O. N. Zakharova and we have identified deposits. Gold facies in nearshore sand bars and deposits of the small fans reworked by the Devonian sea. These and others represent lenticular, thickened portions of the productive, thin (<0.5 m) beds of shallow water facies, poor in gold occurred in the intervening wide zones.

The gold-bearing fans are 1-3 km wide; the enclosing deposits 3-5 m thick, rarely reaching 9 m. Fans occur in chains along the base of ancient structural ledges along ancient faults that intersect the pre-Yaransk sediment blanket. The gold- and diamond-bearing sediments were transported by small streams from local ridges of the Baikal basement, with fragments of the thin sediment blanket of the late ordovician(?) and Pizhensk Formation. These sediments were intermediate depositories of placer gold. At the time the Yaransk Formation accumulated, they were major sources of the paleo-placers. This is confirmed by the dominance of "worn" gold in basal horizons; indicative of intensive supergenetic reorganization and development in the pre-Yaransk placers. Calculations indicated that despite the small gold content of the intermediate gold deposits, erosion of even small (5×10 km; 15 m thick) fragmental lithosomes of the deposits freed large gold volumes. These were subsequently incorporated into the ancient placer deposits.

Fan-shaped gold distribution patterns occur in alluvial fan braids of the Witwatersrand and Tarkwa gold deposits. Gold was preserved, despite subsequent reworking of the alluvial fan deposits in the surf zone (Fig. 5). The first-order gold-enriched braid channels were 1.3 km long and 170-250 m wide. Four-to-five braid channels existed in each studied fan. As in the Tarkwa fans, the most productive ones occupied central positions [19, 40, 41]. Their interior includes second and third order gold placer lithosomes, separated by zones of low gold concentration. Their gold concentrations are identical to those found in rudites of known foreign deposits. Gold concentrated in the basal bed of the producing horizon, deposited on uneven surfaces of the Baikal basement or Lower Ordovician(?) and Middle Devonian(?) sandstones. The basement surface was pockmarked by "pockets" of deep depressions and fractured (Fig. 6). Gold enrichment of the lower bed apparently was related to gold deposition, associated with partial or complete reworking of deposits from old alluvial fans. Consequently, the higher conglomerate and gritstone beds in the producing horizon contain less gold than the lower beds do. Locally, high gold concentrations have been found in sands as well. These sands separate the basal conglomerate bed from the second bed in the middle interval of the producing horizon. Gold concentrates at the base of the basal rudite bed as natural placer concentrate with ilmenite, columbite, monacite, kularite, florencite, zircon, leucoxene, and ilmenite. Less frequently, disseminated gold evenly and thoroughly impregnated the maximum 1-m-thick basal bed.

In areas of wedge-outs of gold-bearing areas where cross-stratified sands overlie placer beds, the underlying units include very thin (maximum 0.5 mm) gold laminae, derived from 0.05-0.2 mm placer layers. Our findings in this regard agree with those of Zakharova and G. V. Kuznetsova. The laminae in particular reefs in a number of Witwatersrand deposits [36] were distributed, similarly to gold layers on unconformity surfaces. 1-2 cm thick layers formed the sets. Such minisets that occupy 2-3 m² areas contain very high gold concentrations. Judging from the direction of cross lamination, these lace-shaped gold layers on the ledge slopes of the placer beds were formed by erosion and transport by strong currents. Thus, the laminae represent data from an exploration trench that cuts through a first-order gold seam in an alluvial fan, with drillcore data, indicated that the correction factor was 6-8; in certain locations as high as 10! Such data are essential in evaluating conglomerate prospects in other Russian area, including the KMA, and Karelia. Despite minute gold particle sizes, primary placer gold, although to greatly different extent, is always unevenly distributed in stratiform deposits, [1, 4, 5, 9, 15, 16, 19, 23, 26, 34, 35, and 42].

In addition to the investigated, more interesting and typical region in Russia, conglomerates with significant gold content also occur in the pre-Sayan and Kozhimsk Uplifts of the polar Ural region, the Yenisei Ridge, the western and eastern slopes of the Aldan Shield, the flanks of the Tonod Anticlinorium of the Patom Uplands, as well as in the Olenek Uplift of the Siberian Platform, in its eastern (Gornostakh Anticline of the Kyllakh Uplift and the Bilyakchan Uplift) and

the northern (northeastern Taimir) folded margin belt. Table 2 provides a brief description of the auriferous conglomerates in this region.

(1). Comparison of gold-bearing conglomerates of different tectonic settings in Russia with ore-reefs of commercial deposits abroad, indicates their essential similarities. The geological conditions of formation and distribution of ore-conglomerate bearing varieties, their alteration in time, the composition and lithology of the producing horizons have been found to be essentially identical. Independently of age, local units, such as gold fields and potential gold-bearing areas greatly resemble typical structural traps, including rigidly defined ore-bearing facies, the governing principles of gold distribution within the field and in the conglomerate layers. Such similarities also apply to the gold characteristics (particle size, sample analysis results, morphology, etc.). These facts indicate that conditions had been favorable for gold concentration in conglomerates in the discussed Russian areas.

(2) In contrast with earlier publications, identification of categories of geological objectives, corresponding to gold-bearing regions, fields, and deposits provide new means for generalized conclusion. This opens up new vistas for exploration in the studied region, involving potential gold fields, similar to those found in the central Timan area. In addition to the similarity with the geological composition of foreign gold fields, the potential of prospective fields is suggested by gold content data. Study of numerous local areas with conglomerates of various ages (Lower and Upper Cambrian, Paleozoic) indicated that the background metal content in the assayed horizons is two magnitude order higher than the Clarke value of the detrital rocks (30-65% of the samples contained 0.2-0.9 g/ton gold). As indicated earlier, with exception of gold ores proper, this value is close to the average value in conglomerate gold reefs of Witwatersrand and Jakobina. Against this background, "signature samples" with locally assayed areas occur in practically all regions. As the Devonian gold-bearing conglomerates of the central Timan basins, they have also been studied in great detail. The results point to Potential commercial gold deposit areas.

(3) Despite the traditional view about the role of early Precambrian conglomerates [19, 24, 26], results of the study of Russian conglomerates indicates a sufficiently high potential. This also applies to lower Precambrian conglomerates (KMA area, Karelia, Patomsk Uplands, etc.), conglomerates of late Precambrian (Riphean and Vendian) and the Paleozoic (Middle Timan, Kozhimsk Uplift, Yenisei Ridge, pre-Sayan area, etc.).

(4) Stratiform gold mineralization predominates over mineral development that occurs in cross-cutting veins. Stratigraphic and lithologic control almost always rules conglomerate-bearing formations, especially in facies and producing horizons. This indicates the primary placer origins of gold in greater part of the conglomerates in prospective areas in Russia, as well as in the reefs of classic foreign deposits.

(5) Remobilization and redistribution of the metal in gold-bearing conglomerates during these processes do take place but their impact remained essentially localized. These are more common in the metamorphosed conglomerate-bearing formation that accumulated in the tectonically mobilized structures: geosynclinal fold belts in ancient basement (synclinal belts of the KMA and other areas), in zones where the cover of the protoplatform was folded (Kozhimsk Uplift, Yenisei Ridge, etc.). In platform covers with horizontal beds mild dislocations did take place (e.g., Timan, etc.), marking primary placer gold genesis, usually preserved in conglomerates.

(6) The most interesting prospects are local structural "traps" in the KMA Block, the graben-syncline structures of the Karelian Massif and the platform cover of the Central Timan. Judging by the similarity of the traps and the ore-enclosing facies in the first two areas, with foreign conglomerate-gold deposits, of the early Precambrian, one may count on the discovery of gold and Au-U fields of large and intermediate dimensions. In Devonian units of the Central Timan and the Riphean, Vendian, and Paleozoic conglomerates of poorly studied Ural and Siberian areas there is hope for the discovery of smaller, but more numerous gold deposits. Such deposits, in our view, are typical of the late Precambrian and Phanerozoic.

LITERATURE CITED

1. A. I. Bezgubov, Yu. I. Byvshikh, P. K. Dement'ev, et al., Uranium in Ancient Conglomerates [in Russian], Atomizdat, Moscow (1963).
2. I. S. Vasserman, V. P. Dmitriev, and N. D. Kononov, "Prediction and exploration methods in search for mineral deposits in the Voronezh crystalline massif," in: Methods of Prediction and Exploration of Mineral Deposits In The Voronezh Crystalline Massif [in Russian], Izd-vo Mingeo RSFSR, Moscow (1989), pp. 15-22.

3. P. K. Dement'ev and V. G. Kruglova, "Aspects of the geologic positions and types of ancient metal-bearing conglomerates," in: Problems of Metal Content of Ancient Conglomerates in the USSR [in Russian], Nauka, Moscow (1969), pp. 53-58.
4. Yu. A. Deryugin, "New data on the genesis of gold and uranium ores in conglomerates of Witwatersrand deposits," Trudy VIEMS, Ékspress-inform., EI VIEMS, Ser. "Geologiya- Exploration Methods of Ore Deposits," No. 1, 1-10 (1983).
5. T. P. Zhadnova, L. S. Kut'yurina, A. S. Lobanov, et al., "Gold content of Precambrian conglomerates of the Patomsk Uplands and its associated zones in the Aldan Shield," in: Problems of Metal Content of Ancient Conglomerates in the USSR [in Russian], Nauka, Moscow (1969), pp. 154-161.
6. V. I. Kazanskii, N. P. Laverov, and A. I. Tugarinov, Uranium Ore Genesis [in Russian], Atomizdat, Moscow (1978).
7. N. D. Kononov, "Basic principles of gold mineral distribution patterns in coarse detrital rocks of the basal Proterozoic horizon, Kursk Magnetic Anomaly area," in: Precambrian Metal Mineralization [in Russian], Abstracts of the First All-Union Meeting on Precambrian Metal Genesis [in Russian], Leningrad (1975), pp. 129-131.
8. A. A. Konstantinovskii, "Geology and metal content of Precambrian terrigenous quartz beds," Byull. MOIP Otd. Geol. 60, No. 3, 36-50 (1985).
9. A. A. Konstantinovskii, V. I. Levin, and S. V. Yablokova, "Origin of gold in Precambrian conglomerates, northeastern Siberian Platform," Izv. Akad. Nauk SSSR, Ser. Geol., No. 12, 147-150 (1981).
10. A. A. Konstantinovskii, V. M. Pachukovskii, and O. N. Zakharova, "Problems of gold content in the Timan," Litol. Polezn. Iskop., No. 5, 69-80 (1993).
11. A. A. Konstantinovskii and B. I. Prokopchuk, "Middle Devonian quartz sand formation, east rim of the Russian Platform," 8th All-Union Meeting on Placer Geology, Abstracts [in Russian], Kiev, 119-130 (1987).
12. A. A. Kotov, V. I. Povonskii, and B. A. Yatskevich, "Metal-bearing conglomerates from part of the East European Platform," 8th All-Union Meeting on Placer Geology [in Russian], Abstract, Kiev (1987), pp. 176-178.
13. F. P. Krendelev, Metal-Bearing Conglomerates of the World [in Russian], Nauka, Novosibirsk (1974).
14. E. M. Krestin, "Composition and potential ore content of the Archean greenstone belt, Kursk-Voronezh Crystalline Massif," in: Precambrian Rift Structures of the Baikal-Amur Region and Their Metal Genesis [in Russian], Nauka, Novosibirsk (1985), pp. 170-176.
15. V. Z. Negrutsa and T. F. Negrutsa, "Lithology and formation conditions of Proterozoic Quartz Conglomerates in Karelia and their gold content," Litol. Polezn. Iskop., No. 6, 41-53 (1965).
16. G. V. Nesterenko, Origin of Placer Deposits [in Russian], Nauka, Moscow (1977).
17. I. I. Ovsyannikov, L. S. Barokha, B. A. Yatskevich, et al., "Composition and probable sources of polymetallic placer deposits in an East European Platform area," 8th All-Union Meeting on Placer Geology, Abstracts [in Russian], Kiev (1987), pp. 187-188.
18. G. V. Pisemskii, L. M. Ganzha, and N. Ya. Bolotova, "Preliminary data of the investigation of gold content in Precambrian conglomerates, areas of Krivoi Rog and the Kursk Magnetic Anomaly," in: Problems of Metal Content in Ancient Conglomerates in the USSR [in Russian], Nauka, Moscow (1969), pp. 101-113.
19. D. A. Pretorius, "Gold and uranium in quartz conglomerates," in: Ore Deposit Genesis [Russian translation], Vol. 2, B. Skinner (ed.), Mir, Moscow (1984), pp. 5-38.
20. D. S. Robertson, "Basal Proterozoic beds; ancient marker horizons and their use in uranium exploration (a summary report)," Formation of Uranium Deposits [Russian translation], Mir, Moscow (1976), pp. 507-526.
21. I. S. Rozhkov, "Proterozoic gold-bearing conglomerates and their use in uranium explorations, Republic of Ghana," Geol. Geofiz., No. 1, 60-74 (1967).
22. I. B. Flerov, S. S. Kal'nichenko, A. A., Konstantinovskii, et al., "Evolution of the placer development process in Earth's history; by the example of gold placers," in: Development of ore Deposits [in Russian], Abstracts of Papers by Soviet Geologists, 28th International Geological Congress, G. V. Ruchkin (ed.), Moscow (1989), pp. 110-117.
23. F. L. Hess, "Sedimentary U, V, Ag, Au, Rn, and Mo deposits," Geology of Ore Deposits of Western States in the USA [Russian translation], Moscow-Leningrad (1937), pp. 375-407.
24. S. D. Sher, Gold Metallogenesis; Europe, Africa, and South America [in Russian], Nedra, Moscow (1974).

25. V. V. Yakovleva, B. N. Shustov, and Z. P. Mirolyubova, "The gold potential of Precambrian conglomerates in Karelia," in: Problems of Metal Content in Ancient Conglomerates in the USSR [in Russian], Nauka, Moscow (1969), pp. 95-101.
26. R. W. Boyle, "The geochemistry of gold and its deposits," Bull. Can. Geol. Survey, No. 280, 1 (1979).
27. P. E. Cloud, "Atmospheric and hydrospheric evolution of the primitive Earth," Science, **160**, 729-736.
28. W. H. Cox, "Regional environment of the Jakobina auriferous conglomerate, Brazil," Econ. Geol., **62**, No. 6, 773-780 (1967).
29. W. H. Gross, "Evidence for a modified placer origin for auriferous conglomerates, Canavieiras mine, Jakobina, Brazil," Econ. Geol., **63**, No. 3, 271-276 (1968).
30. D. K. Hallbauer and T. Utter, "Geochemical and morphological characteristics of gold particles from recent river deposits and the fossil placers of the Witwatersrand," Min. Depos., **12**, 293-306.
31. D. K. Hallbauer, "Witwatersrand gold deposits, their genesis in the light of morphological studies," Gold. Bull., **2**, No. 1, 18-31 (1978).
32. I. Harkonen, "The gold-bearing conglomerates of Kaarestunturi, central Finnish Lapland," in: Gold-82. The Geology, Geochemistry and Genesis of Gold Deposits. Balhems, Rotterdam (1982), pp. 239-247.
33. N. R. Junner, T. Hirst, and H. Servis, "The Tarkwa gold field," Gold Coast Geol. Survey Mem., No. 6 (1942).
34. W. E. L. Minter, "Gold distribution related to the sedimentology of a Precambrian Witwatersrand conglomerate, S. Africa, as outlined by moving-average analysis," Econ. Geol., **65**, 963-969 (1970).
35. W. E. L. Minter, "A sedimentological synthesis of placer gold, uranium and pyrite concentrations in Proterozoic Witwatersrand sediments," in: Fluvial Sedimentology, A. D. Miall (ed.), Canada Soc. Petroleum Geologists, 801-829 (1978).
36. A. D. Pretorius, "The nature of the Witwatersrand gold-uranium deposits," in: Handbook of Strata-bound and Stratiform ore Deposits, Elsevier Sci. Publ. Co., Amsterdam, Chap. 2, 29-88 (1976).
37. D. A. Pretorius, "The goldfields of the Witwatersrand basin," Geol. Soc. South Africa, 489-493 (1986).
38. R. Saager, T. Utter and M. Meyer, "Pre-Witwatersrand and Witwatersrand conglomerates in South Africa: a mineralogic comparison and genesis of gold-uranium placers," in: ore Genesis, Springer Verlag, Heidelberg (1982), pp. 213-220.
39. G. Sestini, "Sedimentologic study of the Tarkwaian gold deposits," 14th Ann. Report. Res. Inst. Afr. Geol., Univ. Leeds, 38-45 (1971).
40. G. Sestini, "Paleocurrent and exploration for gold in the Tarkwaian of Ghana," 15th Annual Report, Res. Inst. Afr. Geol., Univ. Leeds, 27-41.
41. P. R. Simpson, "Detrital uraninite and pyrite: are they evidence for a reducing atmosphere? Genesis of uranium and gold-bearing Precambrian quartz-pebble conglomerates," U.S. Geol. Survey Prof. Paper, 1161, 211-219 (1981).
42. N. D. Smith and W. E. L. Minter, "Sedimentological controls of gold and uranium in two Witwatersrand paleo-placers," Econ. Geol., **75**, No. 1, 1-14 (1980).
43. T. Utter, "Rounding of ore particles from the Witwatersrand gold and uranium deposits (S. Africa), as indicator of their detrital origin," J. Sediment. Petrol., **50**, 6-71 (1980).

ISOTOPIC COMPOSITION OF OXYGEN IN DANBURITES FROM LATE-JURASSIC GYPSUM – ANHYDRITE ROCKS OF SOUTHEASTERN TURKMENISTAN

V. N. Svedov and Z. D. Kuliev

UDC 550.4:552.53(575.4)

In contrast to the isotopic composition of boron, study of which has made it possible to determine peculiarities of the formation and the sources of material for a number of natural borates and borosilicates [6, 7], the isotopy of oxygen in them has not been studied much. Such research can be of interest not only in regard to genesis, but also for evaluating the scale of development of scarce boron raw material at occurrences of it. It is known, in particular [6], that the value of $\delta^{18}\text{O}$ in datolite from large alpine skarn deposits is negative; and from small ones it is positive, and in the danburite of small deposits the oxygen is even heavier.

The borosilicate danburite, in the form of unevenly dispersed, rounded and elongated, white inclusions and dusty impregnation, often outlined by a fringe of hydroxides and idiomorphic carbonate crystal particles, is observed in subsalt, suprasalt, and peripheral gypsum – anhydrite complexes of potassium-bearing formations [2–4, 8]. In southeastern Turkmenistan, boron-bearing gypsum anhydrites of the lower Gaurdak subsuite, of Kimmeridgian-Tithonian age, which include lenses of water-transparent rock salt, interlayers of marking limestone-dolomite rocks of horizons R in the middle part, and silica concretions, lie on rocks of Oxfordian carbonate strata and are covered by potassium-chloride deposits of the upper Gaurdak subsuite [1]. They emerge to the ground surface within the contours of the Gaurdak and Kugitang anticlines and are easily traced in well cores under younger formations. The isotopic composition of oxygen in samples of danburite, chalcedony, and carbonates that we took in field investigations was measured by B. G. Pokrovskii in the isotopic-geochemistry laboratory (Geological Institute of the Russian Academy of Sciences) on an MI-1201 V instrument. The error in determining $\delta^{18}\text{O}$ does not exceed $\pm 0.2\%$. Oxygen was obtained from the silicates as a result of a reaction with ClF_3 at 400–500°C, and then converted to CO_2 by a reaction with graphite in the presence of platinum at 600–700°C. Carbonates were decomposed with orthophosphoric acid. It was established that the oxygen in the studied samples is heavily enriched with the ^{18}O isotope.

According to the values of $\delta^{18}\text{O}$ and other characteristics of the structure and composition, it seems possible to distinguish the following morphogenetic groups: 1) sedimentation-diagenetic and 2) epigenetically altered (Table 1).

In the first group, we classified samples of danburites, and Oxfordian and Kimmeridgian – Tithonian limestones with values of $\delta^{18}\text{O}$ of 29.7–33.2‰, the formation of which occurred in a salinizing sea in conditions of isotopic equilibrium of the water and sediment. From normal marine oolitic-coprolitic limestone to stromatolitic limestone slightly sulfated in the stage of diagenesis there is an increase in $\delta^{18}\text{O}$ from 30.7 to 32.1‰, respectively, displaying a quite definite tendency toward heavier isotopic composition of oxygen as the seawater condenses. The limestones have values of $\delta^{13}\text{C}$ of 3.2–3.4‰, which are characteristic, in general, of unaltered sedimentary carbonate rocks in the region [5]. The sole find of a danburite concretion exposed in rock salt has an isotopic composition of oxygen close to the limestones ($\delta^{18}\text{O}$ 33.2‰). Some enrichment of it with ^{18}O is explained by the fact that, even in similar conditions of sedimentation, the oxygen in silicates is usually heavier than in carbonates. Based on the limits of variation in $\delta^{18}\text{O}$ in the described samples of danburite and limestones, we also classified in this group danburites with values of $\delta^{18}\text{O}$ of 29.7 and 30.1‰. The data obtained on the described group of specimens allows us to state that part of the danburite inclusions is practically unaffected by subsequent processes of lithogenesis of the sedimentation-diagenetic concretion.

In the group of epigenetically altered minerals, the authors classify a sample of siliceous concretion ($\delta^{18}\text{O}$ 22.1‰) from sulfur gypsum anhydrite, and also the greater part of the danburite specimens, with $\delta^{18}\text{O}$ from 25.9 to 28.6‰. Visually, signs of secondary change in the silica concretions are expressed in an occasionally found concentric-zonal structure, on account of alternation of siliceous and gypsum zones; and under a microscope, in enlargement of their

TABLE 1. Results of Isotopic Analyses of Silicate Minerals and Carbonate Rocks

Specimen number	Minerals, rocks	$\delta^{18}\text{O}$, ‰	$\delta^{13}\text{C}$, PPT
Sedimentation-diagenetic			
122	Danburite with anhydrite in rock salt (59)	33.2	—
117	Stromatolitic wavy-bedded limestone, R horizon J ₃ km-1 (293/III)	32.1	3.2
116	Oolitic-coprolitic limestone, J ₃ ox (293/III)	30.7	3.4
33	Danburite in gray gypsum anhydrite, 20 m above the R horizon (1761/V)	30.1	—
2	Danburite in white gypsum, northwestern part of the Southern quarry	29.7	—
Epigenetically altered			
119			
114	Danburite in gray, fine-latticed, lumpy gypsum anhydrite (446/IV)	28.6	—
120	Danburite in dark-gray gypsum anhydrite (293/III)	27.9	—
6	Danburite in gray, lumpy gypsum anhydrite (464/I)	27.8	—
7	Danburite in light-gray gypsum anhydrite (1951/V)	27.7	—
113	Danburite in light-gray gypsum anhydrite (15 m above the head of well 1951/V)	26.8	—
115	Danburite in gray, lumpy gypsum anhydrite (308/II)	25.9	—
	Siliceous concretion in gray gypsum anhydrite, 30 m above the roof of J ₃ ox (293/III)	22.1	—

cryptomerous structure in individual sections. In borosilicate inclusions, with a dense outward appearance, microscopic cracks are manifested, radially developed from numerous centers and forming rosettes in the mass of the danburite. And the carbonate-hydroxide fringes around borosilicate nodules are obviously due to postsedimentation processes.

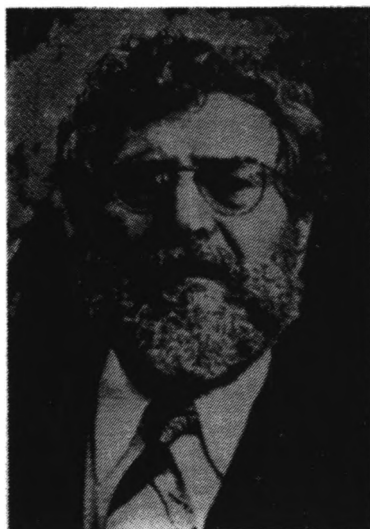
The isotopic composition of oxygen in epigenetically altered concretions was determined, in our opinion, by the occurrence in the sediment of normal colloidal solutions (sols) and subsequent changes in them. We have to suppose that the final formation of the studied concretions apparently took place in the postsedimentation stage from a sol silicate substance that lost a significant part of its water and changed into hydrogels, and was devitrified in harsher thermodynamic conditions than in diagenesis. Removing cations, the segregated solution entered into interaction reactions with the surrounding rock, forming a carbonate-hydroxide fringe.

The catagenetic processes as a result of which danburite concretions were transformed did not lead to intensive migration and redistribution of boron, as a result of which secondary significant concentrations of boron minerals could appear.

LITERATURE CITED

1. A. A. Baikov, K. P. Berkeliev, B. P. Zhdanov, et al., *Geology and Mineral Resources of the Gaurdak-Kugitang Region of the Turkmen SSR* [in Russian], Izd-vo Rostov. Un-ta, Rostov-na-Donu (1974).
2. S. M. Korenevskii, *The Set of Mineral Resources in Halmeic Formations* [in Russian], Nedra, Moscow (1975).
3. S. S. Korobov, S. V. Malinko, and V. I. Sedlitskii, "New data on boron mineralization in anhydrite strata of Central Asia," *Zap. VMO*, **94**, No. 6, 719-726 (1965).
4. V. M. Kuligina, G. M. Drugov, and Ya. Ya. Yarzhemskii, "Danburite and strontium hilgardite in Lower-Cambrian salt-bearing deposits of Eastern Siberia," *Dokl. Akad. Nauk*, **171**, No. 3, 710-712 (1966).
5. I. S. Lazarev, G. P. Mamchur, G. M. Vdovichenko, et al., "The origin of carbonate rocks of Upper-Jurassic halmeic and carbonate formations of the Gaurdak-Kugitang region according to the isotopic composition of carbon," *Litol. Polezn. Iskop.*, No. 6, 132-137 (1978).
6. S. V. Malinko, A. E. Lisitsyn, and L. V. Sumin, "Isotopic composition of boron in natural borates with borosilicate as an indicator of the conditions of their formation," *Dokl. Akad. Nauk*, **267**, No. 2, 453-456 (1982).
7. S. V. Malinko, A. E. Lisitsyn, and L. V. Sumin, "Isotopes of boron in minerals — indicators of the source of ore material," *Sov. Geol.*, No. 3, 89-97 (1987).
8. V. A. Cherepanov, "Danburite diagenetic concretions in Devonian suprasalt strata in the northern part of Siberia," *Dokl. Akad. Nauk*, **1**, No. 4, 974-975 (1965).

IN HONOR OF THE EIGHTIETH BIRTHDAY OF A. B. RONO



On December 16, 1993, the prominent geochemist, lithologist, and paleogeographer, Academician of the Russian Academy of Sciences, Professor Aleksandr Borisovich Ronov was 80 years old. Having begun his working life at the Khar'kov electromechanical plant and graduated from the industrial-training school there, A. B. Ronov was interested in getting to know the work of physicists at the High-Voltage laboratory of the Ukrainian Physicotechnical Institute, to which he was sent by the plant on a business trip as a mechanic. At that time, he tried his hand at literature, publishing essays and poems, and he was admitted to the Russian section of the Union of Proletarian Writers of Ukraine.

While preserving his love for literature, A. B. Ronov chose the difficult path of a geologist. In 1933, he entered the geology department of Khar'kov University, from which he transferred, after two years, to Leningrad State University, from which he graduated in 1938, majoring in "geochemistry." After graduation, A. B. Ronov worked as a geologist for the Leningrad Geological Administration engaged in geological surveying and study of processes of metamorphism and granitization in Karelia. In 1939, on the recommendation of his teacher, Academician F. Yu. Levinson-Lessing, A. B. Ronov became a graduate student at the Radium Institute of the Academy of Science of the USSR, in the laboratory of V. V. Belousov.

During the Great Patriotic War, A. B. Ronov, participated in work on surveying and studying the "Second Baku" oil fields as part of the Volga-Bashkir expedition of the Council on Study of Productive Forces of the Academy of Sciences of the USSR. In 1943, he defended his candidate's dissertation, after which he was appointed leader of the Saratov gas expedition of Glavgaztopprom with the Council of People's Commissars of the USSR, conducting work on surveying gas fields in the Volga and Transvolga regions. In later years, A. B. Ronov continued to participate in exploratory work for oil and gas as part of the Azerbaidzhani oil expedition of the Council on Study of Productive Forces of the Academy of Sciences of the USSR, combining that work with scientific research in the field of tectonics, lithology, and paleogeography.

In 1944, Academician O. Yu. Shmidt invited A. B. Ronov to study for his doctorate degree at the Institute of Theoretical Geophysics of the Academy of Sciences of the USSR. There, he researched in detail sedimentation and the tectonic history of development of the European territory of the USSR, which led him to create the volume method, which became widely known and laid the foundation for a system of quantitative methods. In later years, comprehensive investigations of the history of sedimentation within the bounds of large regions (the Russian platform, Caucasia, the Urals, etc.)

Editorial staff of the journal *Lithology and Mineral Resources*; Interinstitutional Lithological Committee of the Russian Academy of Sciences. Translated from *Litologiya i Poleznye Iskopaemye*, No. 2, pp. 138-139, March-April, 1994.

were conducted under his leadership and with his direct participation. These works continue to the present time at the V. I. Vernadskii Institute of Geochemistry and Analytic Chemistry of the Russian Academy of Sciences, where A. B. Ronov has worked since 1950, and in 1954 he created the laboratory of geochemistry of sedimentary rocks. The research conducted there is based on an enormous amount of data on the lithology, mineralogy, and chemical composition of sedimentary rocks of various ages and geneses. The geological basis for the geochemical calculations was a series of lithological and paleogeographic maps of large regions: the Russian platform, its geosynclinal border, and, finally, the territory of the whole former Soviet Union, where were published in the form of three atlases (1953, 1961-1962, and 1967-1969). A. B. Ronov was one of the initiators, leaders, and direct authors of these works, which were conducted by an enormous collective of Soviet geologists, with the participation of specialists from the socialist countries. One of the atlases, "Atlas of the USSR," was named the "Soviet stratigraphic companion" by American specialists. Together with Academician V. E. Khain, A. B. Ronov developed the theoretical principles for constructing maps of lithological formations of the world for the Earth's continental block, as well as for the World Ocean, beginning from the Upper Jurassic. On the basis of these maps, the volumes of the "Atlas of Lithological and Paleogeographic Maps of the World" were compiled, the first of which came out in 1984 ("Late Proterozoic and Paleozoic of the Continents"); and the second, in 1989 ("Mesozoic and Cenozoic of the Continents and Ocean").

The volumes of sedimentary and volcanogenic rocks and sediments of different geneses deposited in various stages of development of the sedimentary mantle within the bounds of each of the continents and in various parts of the World Ocean were calculated from the maps that were compiled. These fundamental empirical evaluations, being unique, aroused enormous interest in the geological community after their publication and were the practical basis for construction of global models by Russian and foreign geologists, geochemists, and paleoclimatologists.

These summaries of a large amount of factual data served A. B. Ronov and his co-workers as the basis for global geochemical and paleoclimatic constructions.

A. B. Ronov's widely known discussion with Academician N. M. Strakhov led to a clearer formulation and substantiation of certain principles of the quantitative approach to investigation of the sedimentary process, i.e., to intensification and development of quantitative methods, the introduction of which to the geological sciences was enthusiastically promoted by A. B. Ronov.

Using data from evaluation of the masses of carbonate rocks accumulated in the sedimentary mantle in various stages of the Phanerozoic, and also data that he obtained on the masses of organic matter, A. B. Ronov, together with Academician M. I. Budyko, developed a model of change in the contents of carbon dioxide and oxygen in the Earth's atmosphere in the Phanerozoic. This model, which uses V. I. Vernadskii's ideas, and also factual data and analysis of the geochemical cycles of carbon and oxygen on which it is based, was the content of the monograph "History of the Earth's Atmosphere," published in 1985 together with M. I. Budyko and Academician A. L. Yanshin, which was immediately translated into English, Japanese, and Chinese.

Together with Academician A. P. Vinogradov, and then with his coworkers, A. B. Ronov performed basic research on the evolution of the chemical composition of basic types of sedimentary rocks in the course of geological history, on the chemical structure of mantles of the Earth's crust, on comparative investigation of the history of geochemical processes within the bounds of platforms and geosynclines, on the evolution of volcanism on the continents and in the oceans, and on the history of formation of the composition of atmospheric gases and ocean waters.

Many of the investigations of A. B. Ronov and his school on the geochemistry of a number of individual elements in the sedimentary process (manganese, phosphorus, carbon, hydrolysate elements, radioactive and rare-earth elements, lithium, etc.), and on the geochemistry of stable isotopes of carbon, sulfur, and oxygen were innovative.

These diverse developments led A. B. Ronov to a definite concept of the geochemical evolution of the Earth's outer mantles, in which various factors — tectonic, paleogeographic, plutonic volcanism, and, finally, life — were causally connected, forming the complex dynamic system of the Earth's biosphere. In this way, A. B. Ronov's concept develops V. I. Vernadskii's teaching about the biosphere and fills it with a large amount of important empirical data.

The works of A. B. Ronov and his school, his ideas and methodological approaches, and fundamental factual data are widely known and highly regarded all over the world.

In the last decade, A. B. Ronov has performed a series of generalizing works that are highly regarded by the scientific community. Besides the books and atlases already mentioned, these are his work on coordinated geochemical trends in the most important types of sedimentary and magmatic rocks in the Earth's history, which established evolutionary changes in the composition of the plutonic material that forms the Earth's crust and sedimentary mantle (1992), a

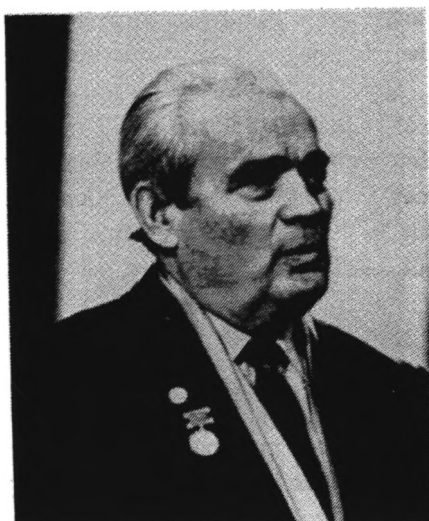
summary on the geochemical cycle of sulfur and its isotopes in the sedimentary mantle and the Earth's crust (1983), the book "Chemical Structure of the Earth's Crust and the Geochemical Balance of the Main Elements" (1990), and, finally, the monograph "The Earth's Sedimentary Stratified Mantle," which just recently came out and most fully sets forth A. B. Ronov's views and the enormous amount of factual data obtained as a result of many years of research.

For his contribution to the development of geochemical science, in 1984 A. B. Ronov was awarded the V. I. Vernadskii gold medal. In 1986, the Geological Society of America elected him as an honorary member, and in 1991 the colloquium "Problems of Lithological and Geochemical Evolution of Sedimentary Rocks" was organized in his honor at the Society's annual meeting. In 1992, the Russian Academy of Sciences elected A. B. Ronov as a full member (academician).

Aleksandr Borisovich's colleagues, students, and friends are happy to express their warm regard and enormous respect. We are amazed at the scientific boldness, exceptional determination, and enormous capability of work that have enabled him, along with the performance of many practically important works, to progressively develop the concepts of global geochemistry.

With great pleasure, we congratulate Aleksandr Borisovich on his birthday; we wish him health, strength, and continued enthusiasm and await with great expectation new scientific ideas and outstanding theoretical generalizations.

IN HONOR OF THE SEVENTY-FIFTH BIRTHDAY OF P. P. TIMOFEEV



On November 14, 1993, adviser to the board of directors of the Geological Institute of the Russian Academy of Sciences, doctor of geological and mineralogical science, Professor, corresponding member of the Russian Academy of Sciences, winner of the State Prize of the USSR Petr Petrovich Timofeev was 75 years old.

P. P. Timofeev's facial and formational investigations of Mesozoic and Cenozoic deposits of Tuva, Southern Siberia, Central Asia, the Urals, Caucasus, Crimea, and Ukraine, and also regions of contemporary sedimentation and peat accumulation in the Rioni intermontane trough, the Baltic region, Cuba, and Florida (USA) were a major contribution to the theory and practice of solving problems of lithology and coal geology. In his monographs "The Jurassic Coal-Bearing Formation of the Tuva Trough" (1964), "Geology and Facies of the Jurassic Coal-Bearing Formation of Southern Siberia" (1969), and "The Jurassic Coal-Bearing Formation of Southern Siberia and Conditions of Its Development" (1970), P. P. Timofeev developed the genetic direction in coal geology, suggested a method of detailed lithological and facial study, and formulated the principles of formational analysis of coal-bearing deposits as a method of obtaining historical and geological knowledge about them. In subsequent publications, P. P. Timofeev showed the universality of these methods and their applicability to the whole set of sedimentary formations. In his understanding, lithological and facial investigations are not an end in themselves, but serve as the beginning stage in solving not only particular (lithological, mineralogical, geochemical) problems, but also a number of general geological ones.

P. P. Timofeev's works on formational analysis largely develop the ideas of the founders of this method, Academicians N. M. Strakhov and N. S. Shatskii, corresponding member of the Academy of Sciences of the USSR Yu. A. Zhemchuzhnikov, and other outstanding scientists. P. P. Timofeev sees a formation as a genetically determined geological body connected with a certain structure and stage of development of a particular region. Applying lithological, facial, and formational methods of analysis, P. P. Timofeev revealed details of the internal genetic relations of many geological phenomena characteristic of the Jurassic coal-bearing formation of Southern Siberia. He suggested a new correlation stratigraphic scheme for Jurassic deposits of that region, which reflects the stages of development of features of the structure of formations in individual parts of Southern Siberia. The differentiation of four types of peat accumulation (delta-coastal, delta, river-valley, and lacustrine) is a fundamentally important point. It is of theoretical, as well as practical significance for predicting coal content and planning exploratory works for coal. In 1967, P. P. Timofeev defended his doctoral dissertation on the basis of this monograph, and in 1972 he was honored with the title Laureate of the State Prize of the USSR.

Editorial staff of the journal *Lithology and Mineral Resources*; Interinstitutional Lithological Committee of the Russian Academy of Sciences; Staff members of the Geological Institute of the Russian Academy of Sciences. Translated from *Litologiya i Poleznye Iskopaemye*, No. 2, pp. 140-141, March-April, 1994.

P. P. Timofeev occupies a prominent place among scientists working on problems of the genesis and coalification of organic matter concentrated in coals and dispersed in the sediments and rocks of terrigenous formations. On the basis of specific data, P. P. Timofeev was the first to consider a coal seam as one of the links in processes of formation of coal-bearing formations. This enabled him to reveal, according to data from the Donets basin, the relation of genetic types of coals with the paleotectonic situations of sedimentation and peat accumulation. This relation was subsequently confirmed at other coal-bearing formations in the USSR and foreign countries (the USA, Germany, Great Britain, France, Belgium, etc.) and was the basis for development of the principles of genetic classification of humus coals and explanation of their genesis from a geological standpoint.

The geological genetic classification of humus coals of the USSR constructed by P. P. Timofeev, which was the first one in the world, was adopted by the International Committee on Coal Petrology as the "System of the Geological Institute of the Academy of Sciences, Moscow." The genetic classification of humus coals is a system in which each genetic type of coal is distinguished according to the structure of organic matter and occupies a specific place in it, the genesis of which depends on a combination of the paleogeographic and paleotectonic situations of sedimentation and peat accumulation.

For the last 20 years, P. P. Timofeev has concentrated his scientific activity on solving two fundamental problems. The first of these is connected with the evolution of water basins and continents in the Earth's history and formation of their sedimentary deposits. He is the head of the "Sediments" (lithology) project of the State Program "The World Ocean." One of his main conclusions is that the modern oceans are young (Upper Cretaceous) formations corresponding to the upper stage of development of the free hydrosphere, which is confirmed by many of our own and foreign scientists. The organization of research on compiling detailed paleogeographic maps of the World Ocean has begun. The second problem is the development of teaching about geological sedimentary formations as large sedimentation bodies.

P. P. Timofeev gives a great deal of attention to the training of highly skilled scientific personnel. Under his direct leadership, 25 doctoral dissertations and more than 35 candidate's dissertations have been defended. On his initiative and with his active participation, in 1983 the "Lithology and marine geology" department was organized in the geological faculty of Moscow State University, with a branch at the Geological Institute of the Russian Academy of Sciences. P. P. Timofeev teaches two courses for students: "Teaching about facies and paleogeography" and "Teaching about geological sedimentary formations." He has published about 350 works. He is the author of four and coauthor of seven monographs.

P. P. Timofeev also gives a great deal of attention to scientific organizational work: he is president of the Expert Council on Earth Sciences of the Higher Certification Commission (VAK), the scientific leader of the "Lithology" section at the Geological Institute of the Russian Academy of Sciences, and president of the Specialized Doctoral Scientific Council of VAK with the Geological Institute of the Russian Academy of Sciences (lithology, sedimentary geochemistry, geology of oceans and seas). P. P. Timofeev represents lithology in various organizations in our country — president of the Interinstitutional Lithological Committee of the Russian Academy of Sciences, president of the lithology (sedimentology) section of the National Committee of Lithologists, member of the editorial staff of the journal "Lithology and Mineral Resources," as well as abroad — member of the Council of the International Association of Sedimentologists and member of the bureau of the International Project "Global Sedimentary Geology," and member of the editorial staff of the international journal "Coal."

P. P. Timofeev has been awarded the orders of the "October Revolution" (1978), "Red Labor Banner" (1975), "Friendship of Peoples" (1989), and six medals.

P. P. Timofeev celebrates his birthday in the prime of his life; with all their heart, the lithologists of the Geological Institute of the Russian Academy of Sciences, the Interinstitutional Lithological Committee, and the editorial staff of the journal wish him health and new successes in science!

VLADIMIR VIKTOROVICH BURKOV



On October 11, 1993, Vladimir Viktorovich Burkov died suddenly. He was a leading scientific staff member of the Institute of Mineralogy, Geochemistry, and Crystal Chemistry of Rare Elements (IMGRE) of the Russian Academy of Sciences and the Russian Mineral Resources Commission, candidate of geological and mineralogical sciences, and a well known specialist in the field of geochemistry of rare elements, exogenous minerageny of rare elements, and the geochemistry of sedimentary formations and weathering crusts; he did a lot to develop the raw-material base of rare elements in Russia.

Vladimir Viktorovich was born on January 6, 1932 in Saratov, in the family of a doctor and a teacher of Russian language and literature. In 1949, he finished school and entered Saratov University in the geology department, from which he graduated with honors in 1954, majoring in "geochemistry." After finishing his studies, Vladimir Viktorovich was sent to Moscow at the disposal of the Presidium of the Academy of Sciences of the USSR as a young specialist who had displayed an ability for scientific work. In August 1954, he was assigned to work at the IMGRE as a junior scientific staff member and took part in research on two major extrabureaucratic scientific problems that the Academy of Sciences was working on in those years: the geochemistry of rare elements and patterns of distribution of deposits of mineral resources.

The first significant result of Vladimir Viktorovich Burkov's scientific activity was a fundamental characterization of the geochemistry, mineralogy, and exogenous types of deposits of strontium, an extremely interesting element with contradictory geochemical behavior in endo- and exogenous processes of ore formation, which was in scarce supply for the country's industry in those years.

Based on the results of that research, Vladimir Viktorovich defended his candidate's dissertation in 1963 and published a monograph, which has not lost its scientific significance even now.

In 1970, Vladimir Viktorovich was given the title of senior scientific staff member, and in 1972 he was appointed director of a sector of the IMGRE that mostly worked on exogenous geochemistry and minerageny of rare elements. Vladimir Viktorovich worked in this field at the IMGRE until the last day of his life.

During that period, under V. V. Burkov's leadership, a large set of investigations was conducted in the sector, aimed at providing the country's raw-material base with deposits of a number of scarce rare and dispersed elements: strontium, germanium, boron, rare earths, zirconium, hafnium, niobium, tantalum, etc. The recommendations given by the sector's collective to the Ministry of Geology of the USSR and regional administrations on the direction of geological explorations, prediction, prospecting, and evaluation of objects helped the country's geological service to solve expeditiously the problems facing it and saved hundreds of millions of rubles in conducting geological explorations.

Editorial staff of the journal *Lithology and Mineral Resources*; Interinstitutional Lithological Committee of the Russian Academy of Sciences; Institute of Mineralogy, Geochemistry, and Crystal Chemistry of Rare Elements of the Russian Academy of Sciences and the Russian Mineral Resources Commission. Translated from *Litologiya i Poleznye Iskopaemye*, No. 2, pp. 142-143, March-April, 1994.

In the early 1970's, on the initiative of the Academy of Sciences of the USSR and the Ministry of Geology of the USSR, a high priority was given to work on weathering crusts in Russia, which are an important source of a number of elements, including rare ones. The results of V. V. Burkov's investigations on this problem were partially reflected in a monograph describing laterite weathering crusts of the Kursk magnetic anomaly, which came out in 1976, and in a series of articles devoted to rare-metal-bearing weathering crusts, which were published in 1970-1992.

The main directions of V. V. Burkov's work on this subject were multipurpose use of weathering-crust deposits, shown on the example of kaolin deposits in Ukraine and other objects; new types of rare-metal deposits in weathering crusts, considered on the examples of deposits of rare earths, zircon, hafnium, tin, tungsten, and gold in a number of regions of Russia and the CIS; and the geochemistry of processes of crust formation.

In the last decade, Vladimir Viktorovich gave a great deal of attention to a complex problem of exogenous geochemistry that has very important practical significance: the mobility of elements in exogenous conditions. The practical significance of this problem is due to the fact that in the territory of Russia the resources of large, rich deposits emerging to the surface have almost been exhausted, and the prospects of development of Russia's raw-material base are mostly connected with concealed and buried deposits, prospecting for which is done primarily by geochemical methods with the use of secondary dispersion halos.

To solve this problem, V. V. Burkov developed a fundamentally new concept about the relative geochemical mobility of elements in exogenous conditions, based on comparison of their acid-alkaline properties. This approach makes it possible to consider the possibilities of elements' migration in various specific geological and geochemical situations of the exozone, and to judge more reliably the possibility of discovering buried and concealed deposits according to secondary dispersion halos. It is also promising for studying deposits of the weathering crust proper.

V. V. Burkov's work is characterized by a close relation of theoretical problems and practical tasks. Description of genetic types of strontium deposits is accompanied by practical recommendations for the direction of geological exploration; theoretical study of the geochemistry of rare-earth elements in weathering crusts culminates in recommendations on distinguishing and evaluating deposits of rare earths sharply enriched with individual elements of this group that are in scarce supply in the country.

Vladimir Viktorovich Burkov did not confine himself to scientific office work; he also did a lot of organizational and social work. Thus, for many years he was curator of the Ministry of Geology of the USSR on strontium, zirconium, and hafnium, and participated in the development of a number of industry programs to improve the country's raw-material base. Vladimir Viktorovich was awarded the medal "Outstanding Prospector."

His premature death is a great loss for geology and for his numerous friends and colleagues. The bright memory of him — a wonderful person, prominent lithologist and geochemist, and a man sincerely concerned about improving the raw-material base of Russia — will be preserved in our hearts.

MAGNETOHYDRODYNAMICS*Magnitnaya Gidrodinamika*

Vol. 30, 1994 (4 issues)\$895

MATERIALS SCIENCE*Fiziko-khimicheskaya Mekhanika Materialov*

Vol. 30, 1994 (6 issues)\$1075

MATHEMATICAL NOTES*Matematicheskie Zametki*

Vols. 55-56, 1994 (12 issues)\$1215

MEASUREMENT TECHNIQUES*Izmeritel'naya Tekhnika*

Vol. 37, 1994 (12 issues)\$1215

MECHANICS OF COMPOSITE MATERIALS*Mekhanika Kompozitnykh Materialov*

Vol. 30, 1994 (6 issues)\$970

METAL SCIENCE AND HEAT TREATMENT*Metallovedenie i Termicheskaya Obrabotka Metallov*

Vol. 36, 1994 (12 issues)\$1215

METALLURGIST*Metallurg*

Vol. 38, 1994 (12 issues)\$1150

POWDER METALLURGY AND**METAL CERAMICS***Poroshkovaya Metallurgiya*

Vol. 33, 1994 (12 issues)\$1215

PROBLEMS OF INFORMATION TRANSMISSION*Problemy Peredachi Informatsii*

Vol. 30, 1994 (4 issues)\$895

PROGRAMMING AND COMPUTER SOFTWARE*Programmirovaniye*

Vol. 20, 1994 (6 issues)\$595

RADIOPHYSICS AND QUANTUM ELECTRONICS*Izvestiya Vysshikh Uchebnykh Zavedenii, Radiofizika*

Vol. 37, 1994 (12 issues)\$1215

REFRACTORIES*Ogneupory*

Vol. 35, 1994 (12 issues)\$1085

**RUSSIAN JOURNAL OF
NONDESTRUCTIVE TESTING***Defektoskopiya*

Vol. 30, 1994 (12 issues)\$1345

RUSSIAN MICROELECTRONICS*Mikroelektronika*

Vol. 23, 1994 (6 issues)\$750

RUSSIAN PHYSICS JOURNAL*Izvestiya Vysshikh Uchebnykh Zavedenii, Fizika*

Vol. 37, 1994 (12 issues)\$1215

SIBERIAN MATHEMATICAL JOURNAL*Sibirskii Matematicheskii Zhurnal*

Vol. 35, 1994 (6 issues)\$1345

**SOIL MECHANICS AND
FOUNDATION ENGINEERING***Osnovaniya, Fundamenty i Mekhanika Gruntov*

Vol. 31, 1994 (6 issues)\$1075

SOLAR SYSTEM RESEARCH*Astronomicheskii Vestnik*

Vol. 28, 1994 (6 issues)\$925

STRENGTH OF MATERIALS*Problemy Prochnosti*

Vol. 26, 1994 (12 issues)\$1345

THEORETICAL AND MATHEMATICAL PHYSICS*Teoreticheskaya i Matematicheskaya Fizika*

Vols. 98-99, 1994 (12 issues)\$1125

UKRAINIAN MATHEMATICAL JOURNAL*Ukrainskii Matematicheskii Zhurnal*

Vol. 44, 1994 (12 issues)\$1250

Send for Your Free Examination Copy**Plenum Publishing Corporation, 233 Spring St., New York, N.Y. 10013****In United Kingdom: 88/90 Middlesex St., London E1 7EZ, England****Prices slightly higher outside the U.S. Prices subject to change without notice.**

RUSSIAN JOURNALS IN THE PHYSICAL AND MATHEMATICAL SCIENCES

AVAILABLE IN ENGLISH TRANSLATION

ALGEBRA AND LOGIC

Algebra i Logika

Vol. 33, 1994 (6 issues)\$860

ASTROPHYSICS

Astrofizika

Vol. 37, 1994 (4 issues)\$920

ATOMIC ENERGY

Atomnaya Énergiya

Vols. 76-77, 1994 (12 issues)\$1150

AUTOMATION AND REMOTE CONTROL

Avtomatika i Telemekhanika

Vol. 55, 1994 (24 issues)\$1345

COMBUSTION, EXPLOSION, AND SHOCK WAVES

Fizika Goreniya i Vzryva

Vol. 30, 1994 (6 issues)\$1075

COMPUTATIONAL MATHEMATICS AND MODELING

A translation of selected works in mathematics

Vol. 5, 1994 (4 issues)\$425

COSMIC RESEARCH

Kosmicheskie Issledovaniya

Vol. 32, 1994 (6 issues)\$1195

CYBERNETICS AND SYSTEMS ANALYSIS

Kibernetika i Sistemnyi Analiz

Vol. 30, 1994 (6 issues)\$1075

DIFFERENTIAL EQUATIONS

Differentsial'nye Uravneniya

Vol. 30, 1994 (12 issues)\$1250

FLUID DYNAMICS

*Izvestiya Akademii Nauk,
Mekhanika Zhidkosti i Gaza*

Vol. 29, 1994 (6 issues)\$1195

FUNCTIONAL ANALYSIS AND ITS APPLICATIONS

Funktsional'nyi Analiz i Ego Prilozheniya

Vol. 28, 1994 (4 issues)\$895

GLASS AND CERAMICS

Steklo i Keramika

Vol. 51, 1994 (12 issues)\$1215

HYDROTECHNICAL CONSTRUCTION

Gidrotekhnicheskoe Stroitel'stvo

Vol. 28, 1994 (12 issues)\$895

INDUSTRIAL LABORATORY

Zavodskaya Laboratoriya

Vol. 60, 1994 (12 issues)\$1225

INSTRUMENTS AND EXPERIMENTAL TECHNIQUES

Pribory i Tekhnika Éksperimenta

Vol. 37, 1994 (12 issues)\$1295

INTERNATIONAL APPLIED MECHANICS

Prikladnaya Mekhanika

Vol. 30, 1994 (12 issues)\$1215

JOURNAL OF APPLIED MECHANICS AND TECHNICAL PHYSICS

Prikladnaya Mekhanika i Tekhnicheskaya Fizika

Vol. 35, 1994 (6 issues)\$1195

JOURNAL OF APPLIED SPECTROSCOPY

Zhurnal Prikladnoi Spektroskopii

Vols. 60-61, 1994 (12 issues)\$1275

JOURNAL OF ENGINEERING PHYSICS AND THERMOPHYSICS

Inzhenerno-fizicheskii Zhurnal

Vols. 66-67, 1994 (12 issues)\$1250

JOURNAL OF MINING SCIENCE

*Fiziko-tekhnicheskie Problemy Razrabotki
Poleznykh Iskopaemykh*

Vol. 30, 1994 (6 issues)\$1125

JOURNAL OF RUSSIAN LASER RESEARCH

*A translation of articles based on the
best Russian research in the field of lasers*

Vol. 15, 1994 (6 issues)\$565

JOURNAL OF MATHEMATICAL SCIENCES

*A translation of selected Russian works
in mathematics*

Vols. 68-72, 1994 (30 issues)\$2995

LITHOLOGY AND MINERAL RESOURCES

Litologiya i Poleznye Iskopaemye

Vol. 29, 1994 (6 issues)\$1195

LITHUANIAN MATHEMATICAL JOURNAL

Lietuvos Matematikos Rinkinys

Vol. 34, 1994 (4 issues)\$760

continued on inside back cover